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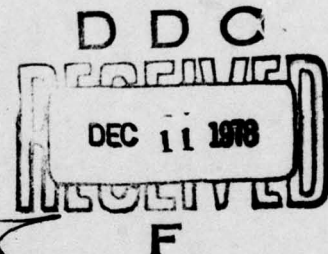
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AN OVERVIEW OF ALTERNATIVE TECHNIQUES FOR
DETERMINING POSITIONS AT SEA, WITH EMPHASIS ON
APPLICABILITY OF POTENTIAL USE FOR POSITIONING BUOYS

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16. Abstract

In support of a Coast Guard effort to improve the capability of field units to place buoys at their assigned locations, an assessment of the potential of alternative techniques for determining position was undertaken. The primary objective of the evaluation was to catalog, in general terms, various field survey techniques of position determination, whether presently in use or in development, with particular emphasis on the general capabilities, limitations, and application of the individual techniques for use in positioning buoys.

The results of this evaluation indicate that no single method can be used to satisfy the varied buoy placement scenarios. Instead, a combination of methods (including those presently used) would be most appropriate. Furthermore, no single combined-methods system would fit all applications unless it consisted of an all-encompassing set of equipments and procedures; an impractical solution.

Laser rangefinder, precision gyrocompass, radiodetermination, and satellite methods are considered to have applicability to buoy placement operations, either as stand-alone or for incorporation with a multi-sensor system. Inertial guidance and underwater acoustic methods are not considered to have practical application.

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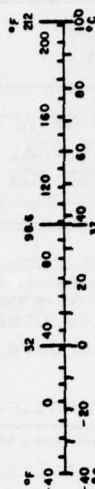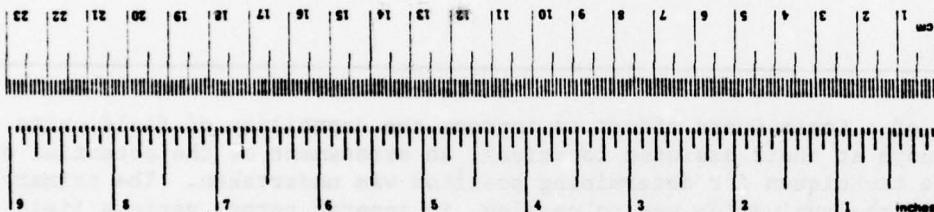Form DOT F 1700.7 (8-72) Reproduction of form and completed page is authorized

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in²	square inches	6.5	square centimeters	cm²
ft²	square feet	0.09	square meters	m²
yd²	square yards	0.8	square meters	m²
mi²	square miles	2.6	square kilometers	km²
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft³	cubic feet	0.03	cubic meters	m³
yd³	cubic yards	0.76	cubic meters	m³
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm²	square centimeters	0.16	square inches	in²
m²	square meters	1.2	square yards	yd²
km²	square kilometers	0.4	square miles	mi²
ha	hectares (10,000 m²)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m³	cubic meters	35	cubic feet	ft³
m³	cubic meters	1.3	cubic yards	yd³
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

EXECUTIVE SUMMARY

A project has been instituted by the Chief, Office of Marine Environment and Systems, U.S. Coast Guard Headquarters, to establish quantitative standards for the positions of short-range aids to navigation, to improve the ability of operating units to position the aids, to improve the reliability of buoys to maintain their positions, and to establish the capability to audit the positions of floating aids at any time after initial placement. The Coast Guard Research and Development Center (R&DC) has been tasked with several aspects of this program, including investigating the use of new methods to establish the positions of aids so that published locations are consistent with actual placement. The Coast Guard Aids to Navigation program manager has identified several contemporary surveying and navigation techniques which are not presently used by buoy servicing units but have potential application to improve the ability of those units to accurately position floating aids to navigation.

A number of techniques were studied. Of these, inertial guidance techniques are considered to be of insufficient accuracy; underwater acoustics techniques are highly impractical from both application and cost standpoints; radiodetermination and laser techniques can provide acceptable accuracies when proper equipment is selected and optimally deployed by knowledgeable personnel; satellite techniques will have a much greater potential in the late 1980's, but present capabilities are limited to periodic availability; and precision gyrocompasses are not sufficiently accurate and are limited by necessary ancillary devices, but can function quite adequately as a support sensor for other techniques (systems).

No single technique, presently available, is suitable for all areas of application. A multi-sensor system, tailored to the application, is the most promising technique in terms of achievable accuracies under the wide spectrum of conditions encountered in buoy positioning.

A concern of the Coast Guard Aids to Navigation program manager is that systems might not be very useful if there exists an inherently high operator-error potential. All of the methods investigated in this report contain systems that are automatically controlled and essentially operator-independent. Advances in micro-processor and mini-computer control have made this method a most practical alternative to other methods which are error-prone and often laborious.

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1.0 INTRODUCTION

A project has been instituted by the Chief, Office of Marine Environment and Systems, U.S. Coast Guard Headquarters, to establish quantitative standards for the positions of short-range aids to navigation, to improve the ability of operating units to position the aids, to improve the reliability of buoys to maintain their positions, and to establish the capability to audit the positions of floating aids at any time after initial placement. The Coast Guard Research and Development Center (R&DC) has been tasked with several aspects of this program, including investigating the use of new methods to establish the positions of aids so that published locations are consistent with actual placement. The Coast Guard Aids to Navigation program manager has identified several contemporary surveying and navigation techniques which are not presently used by buoy servicing units but have potential application to improve the ability of those units to accurately position floating aids to navigation.

The intent of this report, and the style in which it is written, is to paint a descriptive picture of the principles, capabilities, and limitations of the various technologies. It is not written to withstand detailed technical scrutiny. Rather, the information is presented in a manner to make it readable for the many interested Coast Guard officials who have good knowledge of buoy placement operations, but who do not necessarily have a technical background in all of the methods discussed in this report.

1.1 Objective

The objective of this report is to examine contemporary surveying and navigation techniques, to document the state-of-the-art of each, to assess their capabilities and costs, and to make a preliminary assessment of their potential application to the task of positioning buoys.

1.2 Report Organization

The report is divided into several sections, each discussing one potential method of buoy positioning. The sections are: (1) inertial guidance, (2) laser rangefinders, (3) precision gyrocompasses, (4) radiodetermination, (5) satellites, and (6) underwater acoustics. An additional method, multi-sensors, is also included. A description of the development of lines of position for the six positioning methods is given in Appendix A.

Each section of the report incorporates several subsections which are intended to familiarize the reader with fundamentals of operation for each method, describe operating principles and procedures, discuss accuracy considerations indigenous to the method, point out special safety precautions to be observed, describe selected equipments/systems which are commercially available, analyze possible application to buoy tending operations (including suggested scenarios), and draw conclusions concerning useability and/or suitability for buoy placement operations. A glossary is provided to clarify the meaning of many of the technical terms used in the body of the report.

2.0 POTENTIAL SURVEYING AND NAVIGATION TECHNIQUES

2.1 Precision Gyrocompass Methods

2.1.1 Introduction

The Coast Guard presently operates primarily with unstabilized general navigation gyrocompasses aboard its buoy tenders while on the other hand, stabilized gyrocompasses are installed on all larger cutters. These stabilized gyrocompasses are used on the larger vessels not only because they provide improved heading accuracy automatically (compared to unstabilized) during dynamic vessel operations, but also because they provide more precise heading information to the navigation, surveillance and fire control radars.

In the past, the use of general navigation quality gyrocompasses on board Coast Guard buoy tenders has not been considered to create major problems when used for navigation. That is to say, they have been accepted. The gyrocompass input to a position solution was not generally necessary for buoy placement. However, such an input could be a valuable tool if the gyro-compass was to have good "credibility." To increase this credibility, a gyro-compass with better accuracy than that of the general navigation variety is required. Industry can provide several different types of gyrocompasses which offer a many-fold accuracy improvement over those presently used on Coast Guard buoy tenders, and is confidently predicting even better accuracies in the future as new technologies emerge.

2.1.2 History

One of man's oldest navigation instruments is the magnetic compass. Its origin is unknown; however, the eleventh century Vikings are known to have used such a device. Their instrument probably consisted of a magnetized needle which was floated in a container of water. Later, in the fourteenth century, a compass card was added to the magnetic compass.

Although it has retained its importance in navigation, the magnetic compass suffers from its magnetic north seeking characteristic. Since navigators and others had a need for an instrument that indicated true north, researchers set about, early in this century, to develop such an instrument. Their work resulted in the introduction of the gyrocompass, a device which operates on the principle that a rotating mass maintains its orientation in space unless acted upon by some external force. In other words, if the device was set to indicate true north, it would ideally continue to do so unless purposely caused to do otherwise (in practical application the gyro drifts off its initial setting because of such things as mechanical friction, as discussed later).

During 1906-1911, the first successful gyrocompasses were developed nearly simultaneously by H. Anschutz-Kampfe in Germany and E. Sperry in the United States. They both demonstrated that relatively accurate heading information could be obtained in the distorted magnetic field of a steel-hulled vessel.

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After the introduction of the gyrocompass to shipboard use, many types of heading error sources were recognized. These errors were found to be a function of vessel movement and its geographic location (e.g., operating latitude), speed and speed changes, sea-state-induced pitching and rolling, and heading and maneuvering. To offset these errors, modifications were made to the early gyrocompasses. Compensating mechanisms were added to the basic gryo in an effort to reduce each type of systematic error. At first, there was no uniform approach to error compensation as each error was treated individually.

Near the end of World War II, a single device was created to replace the hodge-podge of compensating devices which had been devised to stabilize shipboard aircraft surveillance radar. Originally named a Zenith Meridian Indicator and later renamed the stabilized gyrocompass, it was the first gyrocompass produced with a uniform approach to reducing or eliminating the effects of known gyrocompass error sources. It became the first gyrocompass capable of providing relatively accurate pitch and roll as well as heading information.

2.1.3 Description

A gyrocompass is a device that will seek to indicate true north by taking advantage of gyroscopic characteristics. A precision gyrocompass is one in which this is done in a precise manner. For the purpose of this report, precision is described as more precise than that which is possible with gyrocompass systems presently installed on most Coast Guard buoy tenders. These are generally classed as being for general navigation and are capable of heading accuracies on the order of 0.5 to 1.0 degree.

The heart of a gyrocompass system is a device which either remains angularly fixed in space or precesses in a predetermined manner. This device, called a gyroscope, may be defined as a spinning mass, usually a wheel or disk, turning about an axis and supported by a system which allows the wheel to turn about one or two perpendicular axes when an external force is applied. It is made up of two primary parts, a rotor and a case, which are connected with a gimbal system to allow angular independence between the two.

Two important characteristics of the gyroscope, rigidity and precession, are combined electrically or mechanically with two natural phenomena, gravity and the earth's rotation, to create the basis for the gyrocompass. Rigidity, or gyroscopic inertia, is the tendency of a rotating body to maintain its plane of rotation. When a force is applied to the body, it resists that force and precesses along an axis which is perpendicular to that upon which the force is applied. To illustrate: if a downward force is applied at a point on the rim of the spinning wheel, the greatest amount of downward movement of the mass will be at a point which is 90 degrees ahead of that point in the direction of spin, thus providing an axis shift (e.g., horizontal to vertical) between the applied force and its resultant.

If a simple and, for illustration purposes, perfect gyroscope were to be transported across the earth's surface, two important characteristics would be noted: (1) in response to accelerations, torques would be applied to the gyroscope, causing movement and resulting in a false meridian indication by

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the gyrocompass, and (2) since the gyroscope attempts to maintain its plane of rotation, it would gradually become inclined to the local vertical (referenced to the center of gravity).

In order to overcome the effects of accelerations, a gyroscope must be made non-pendulous. This is accomplished by the use of liquid ballistics, level sensors, or accelerometers. Liquid ballistics are used on the MK14 and MK227 gyrocompasses which are presently installed on many Coast Guard buoy tenders. They consist of two reservoirs of liquid, one mounted on either side of the gyroscope, interconnected by a small tube. The weight is equally distributed above and below the gyroscope's vertical axis. Under acceleration, the liquid is caused to flow between the reservoirs, thereby absorbing the torque and maintaining the stability of the gyroscope. This type of stabilization is characterized by an inherent slow response time and is limited to gyrocompass systems that are designed to tolerate large, so-called ballistic errors (damping errors), e.g., general navigation quality types. A precision gyrocompass, on the other hand, uses either level sensors or accelerometers to simulate the action of a pendulous weight. Both of these devices are characterized by rapid detection of accelerations and the application of a computer-determined compensating torque.

The earth's gravity and the gyroscopic response characteristic of precession are commonly combined to ensure that the gyroscope, and thus the gyrocompass, is always aligned with the local vertical and meridian. This is accomplished by adding a pendulum weight to the gyroscope's horizontal axis at a point which is 90 degrees behind the true vertical, against the direction of spin. Then, as the spin axis starts to incline (due to geographic displacement), the force of gravity acting upon the weight produces a downward torque which causes the gyroscope to turn about its vertical axis and thus maintain meridian alignment. The pendulum weight can be simulated with a computer.

A computer is essential to a precision gyrocompass. It provides a well-regulated, electrical error compensating signal as a substitute for the harsh response that is characteristic of mechanical systems. This compensating signal can (and does) contain correction torques for all known systematic errors, thereby reducing the number of individual error compensating devices. Computer-controlled level sensors or accelerometers are commonly used in those gyrocompasses that are referred to in this report as precision gyrocompasses.

2.1.4 Gyroscope Types

Undesirable gyroscopic precessions are introduced by friction-caused torques in gyroscope suspension systems. As friction is a major error source in gyrocompass systems, considerable effort has been expended on ways to reduce or eliminate it. This has resulted in a number of suspension systems after which the several types of gyroscopes have been named. Examples of these, plus the innovative experimental laser gyroscope are discussed below:

Fluid-Supported Gyroscope

The fluid-supported gyroscope (FSG) is probably the most widely used marine gyroscope. Although mainly used in general navigation gyrocompasses, it has been used in some early precision types.

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The FSG capitalizes on the improvement characteristics of using a larger rotating mass and suspension of the mass in a fluid. A high rotational speed and correspondingly high angular momentum of the larger spinning wheel reduces the effects of bearing friction caused torques. In order to allow the higher rotational speed, the rotor is made part of a gyrosphere which is then immersed in a fluid, e.g., oil or silicone. The weight of the gyrosphere is cancelled by the buoyant force of the fluid.

The FSG suspension method results in several improvements over a straight mechanical system: the load on the vertical axis pivots is eliminated; the horizontal axis load and corresponding bearing friction is reduced; the effects of acceleration is reduced; and mechanical shock protection is afforded.

Flex Gyroscope

The flex gyroscope is characterized by the separation of its flywheel and motor with a flexible shaft or hinge. The motor not being a part of the suspended mass, allows the gyroscope to achieve a high ratio of angular momentum to suspended mass. Motor torques such as bearing friction are decoupled from the flywheel, thus removing a source of undesirable precession.

Gas-Bearing Gyroscope

In the gas-bearing gyroscope, there is no physical contact between the rotor shaft, mating journal, and thrust bearing. When the gyroscope is spinning, the rotor is made to float on a thin film of hydrogen. This nearly friction-free operating environment is further enhanced by the use of so-called precision pivots and jewelled gimbals in gyrocompass systems.

Electrostatically Suspended Gyroscope

The electrostatically suspended gyroscope uses a hollow beryllium sphere as the rotating mass. The sphere is contained in a ceramic envelope enclosed vacuum and is held suspended by the action of electrical attraction between image charges on the sphere and high voltage electrodes contained in the ceramic envelope. Rotational speed exceeding 40,000 r.p.m. is accomplished, in a manner similar to an induction motor, by the use of orthogonally placed spin coils.

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Ring Laser Gyroscope

The ring laser gyroscope (RLG) is classed as a strapdown gyroscope. This means that the gyroscope is mounted directly to the frame of a vessel rather than being in a gimballed system. It is presently in the testing and development stage of production and will not be commercially available for two to five years.

The heart of the RLG is a dual beam laser which is located in one leg of an equilateral triangle formed by a set of mirrors at the adjacent corners and photodetectors at the opposite corner. Angular motion of the device causes the electrical path lengths of the two beams to appear to be different in a manner such as the Doppler effect. That is, a change in beam velocity occurs as a result of motion. The dynamic resultant is recognized as a frequency difference between the two statically equal beams. This frequency difference produces interference fringes which are detected by the photodetectors and translated to equivalent angular motion by the RLG analyzing circuits.

2.1.5 Gyrocompass Configurations

There are three basic gyrocompass configurations. These are gimballed north-seeking, gimballed space stable and strapdown. Gimballed north-seeking gyrocompasses are the only type used in general navigation systems. All configurations are used in various precision gyrocompass systems.

Gimballed North-Seeking Gyrocompass

The gyroscope platform in the north-seeking configuration is electrically or mechanically torqued so as to maintain a continuous true north heading. One or more gyroscopes may be used in the platform. If a single gyroscope is used, the system is termed unstabilized and will provide heading information only. Additional gyroscopes stabilize the platform and can provide pitch and roll information.

Gimballed Space Stable Gyrocompass

This configuration uses two or more gyroscopes to produce a three-dimensional orientation and differs from the north-seeking configuration in that it is not torqued to true north. Instead, the gyroscopes are torqued to some pre-determined heading in inertial space, e.g., celestial reference. Computer transformations are used to present attitude information in selected geographical coordinates.

Strapdown Gyrocompass

As discussed in the preceeding section, the strapdown configuration involves the physical attachment of the gyrocompass platform directly to a vessel's frame. Gimbals are not used and the gyrocompass coordiante system is the same as that of the vessel's, e.g., 000 degrees forward and 180 degrees aft. As in the space stable configuration computer transformations are used to present heading information in selected geographical coordinates.

2.1.6 Operating Principles for Selected Precision Gyrocompasses

A cross section of precision gyrocompasses have been selected for discussion here. Included are the Sperry MK19, MK23, and MK29, the Litton AN/WSN-2, the Rockwell MINISINS the Honeywell SPN/GEANS and the ring laser gyrocompass which is presently under development by several companies. These gyrocompasses range in specified heading accuracies within 1.5 minutes to 1.0 degrees of arc and collectively incorporate all the gyroscopes and gyrocompass configurations previously discussed. Each system has its own special frills that the manufacturer includes as additional selling points, however, only basic operation will be presented here for ease in making comparisons.

The Sperry MK23 offers only a slight improvement in heading accuracy over the MK227, for example. It offers 0.5 degrees r.m.s. specified dynamic precision whereas the MK227 is specified at 0.75 degrees r.m.s. The basis for this gyrocompass is a single fluid-supported gyroscope operated in a gimballed north-seeking configuration. North-seeking is accomplished by the use of level sensors to resolve the force of gravity. Off-null conditions cause the level sensors to develop an error signal which is processed and applied to gyro-torquers to bring the gyrocompass in alignment with the local vertical.

The Sperry MK19 produces a reasonably good dynamic heading precision of about 0.2 degrees r.m.s., but although still available, its manufacturer does not desire to market it any longer as it is becoming outdated. It is a stabilized, gimballed, north-seeking device which uses two gyroscopes and three accelerometers to provide 3-axis (heading, pitch and roll) information. Fluid-supported gyroscopes are used for angular movement detection and the accelerometers are used to detect linear motion. Both angular and linear movement indications are computer processed to develop appropriate alignment torques and attitude information.

The Sperry MK29 and the Litton AN/WSN-2 were competitively developed as a replacement for the aging MK19. Both are similar to the MK19 in that they are stabilized, gimballed, north-seeking and incorporate computer-controlled gyroscopes and accelerometers. The primary difference between the two is that the MK29 uses flex gyroscopes whereas the AN/WSN-2 uses gas-bearing gyroscopes. Both offer heading precisions that are better than 0.1 degrees r.m.s.

Electrostatically suspended gyroscopes (ESG) are being used in two U.S. Navy experimental inertial navigation systems (INS). One is Honeywell's Standard Precision Navigator (SPN/GEANS) and the other is Rockwell's Miniaturized Ship's INS (MINISINS). Although they are INS, both can be used as precision gyrocompasses without incorporating certain hardware and computer software, indigenous to INS. The inertial grade (high-precision) components of both these systems are combined in a computer-controlled, space stable, configuration to provide the best known gyrocompass heading precision, approximately 0.05 degrees r.m.s.

At this point in the development and testing cycle, the Ring Laser Gyrocompass (RLG) is primarily being tested in aircraft INS, but could feasibly be applied to shipboard gyrocompasses or INS. The RLG is another member of the computer-controlled class of gyrocompasses and is projected to provide heading precision and accuracy potential similar to the ESG gyrocompasses noted above.

2.1.7 Operating Procedures for Selected Precision Gyrocompasses

As has been stated before, a computer is essential to a precision gyrocompass. The computer provides an element of control that has been unobtainable with pure electro-mechanical systems. And, it offers a great simplification in start-up and operating procedures.

The MK23 contains the least sophisticated computer and thus the most complicated start-up procedure. Before start-up, the operation switch must be placed in the cage position, the correct latitude entered and the speed unit checked for proper indication of vessel speed (the latter could be accomplished automatically if a speed log input were available). The power is then switched on and the operation switch is turned to the amplifier position. The gyroscope is then manually slewed to the approximate ship's heading. Next, the power switch is turned to the gyro position and after ten seconds the operation switch is put in the uncaged position for ten more seconds before being switched to the level position. The gyrocompass is now allowed time to level itself after which the operation switch is placed in the settle position. Settling is allowed for at least 30 minutes before the operation switch is finally placed in the normal position. At this point, the gyrocompass can be used with reduced accuracy. Maximum accuracy is achievable only after four hours or so of operation. After start-up procedures are completed, the MK23 is essentially a "hands-off" operating system. Only general operating checks need be made periodically.

The MK19 is less complicated to operate than the MK23, but is hampered by earlier computer design technology, mechanical relays and electron tubes. The system is started when the operation switch is placed in the fast settle position and the master switch is placed in the filament position. The filaments are allowed to warm up for 30 seconds before the master switch is placed in the "on" position. The system is allowed to warm up for a further 11 minutes before the gyrocompass is manually slewed to within 10 degrees of vessel heading and the "run" button is depressed. The system then levels and settles for approximately one hour after which the operation switch may be placed in the normal position. Specified accuracy is achieved four hours later

and the only additional operator requirement is to enter any north-south drift which may have occurred during warmup.

The MK29 and AN/WSN-2 have very simple start-up procedures. The operator must simply enter the ship's latitude and turn the system on. All remaining startup operations are completely computer controlled. Both units achieve full accuracy within four hours, with general navigation accuracy available after only 45 minutes.

The operation of the SPN/GEANS is quite similar to that of the MK29 and AN/WSN-2, differing in two notable aspects. Longitude as well as latitude must be entered for start-up and accurate position information must be updated into the system periodically. The periodic update is a requirement for inertial type systems and is further discussed in Subsection 2.3.12.

Start-up and operating procedures for Ring Laser Gyrocompasses have not been set at this point in its development cycle, but simplicity is projected. It is further projected that the RLG will offer near-instantaneous calibration.

2.1.8 Accuracy Considerations

When considering the potential accuracy of a precision gyrocompass system, one must be aware of the major error sources; mistakes by operators, environmental effects of a rotating spherical earth, mechanical constraints, and system resolution. Environmental effects include North-South and East-West speed errors and latitude errors. Mechanical constraints include control system errors and friction errors. Resolution errors result from computer truncation and stepping errors.

Operator Mistakes

Some of the earlier and less sophisticated precision gyrocompasses require a relatively large amount of operator interface, especially during the alignment portion of the start-up procedures. On the other hand, later generation systems require only minimal input from the operator, considerably reducing the potential of operator-induced errors. For the AN/WSN-2, for example, the operator need only enter the correct latitude to start the alignment procedure. The equipment then aligns automatically and can directly input other sensors that require a gyrocompass reference (again, bypassing an operator). Depending upon the method of collecting data for navigation or surveying purposes, an operator may or may not be required to read and transfer heading information to data sheets, in which case data transfer mistakes are possible.

North-South Speed Error - As a gyrocompass is transported in a north-south direction, the stable spin axis would become inclined with the local vertical unless compensation was provided. This basically simple compensation is complicated by error producing torques introduced by the velocity of the transporting vessel. Verticality can be maintained with level sensors or accelerometers and the speed (velocity) error compensated for by providing a speed

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input to the system. The speed input can be applied manually or automatically (e.g., speed log) and must be processed with heading information to determine the actual north-south component of speed when travel is not directly north-south. The appropriate correction component must be applied to all affected gyroscopes. For example, in a two-gyroscope system which is moving along a 045 degrees heading, compensation is equally applied to the heading and pitch gyroscopes for what is termed the north-south speed error.

East-West Speed Error - Any vessel movement, in other than directly north-south, introduces an error in the heading gyroscope that is vectorally additive to the errors induced by the earth rate. In effect, the earth rate becomes faster or slower when the direction of movement is east or west, respectively. As with the north-south speed error, compensation is computer controlled using heading and speed indications.

Latitude Error - When a gyrocompass is operated away from the earth's equator, it becomes affected by the vertical (vertical earth rate) and horizontal (horizontal earth rate) components of the earth's rotational forces. The vertical earth rate causes the spin axis of the heading gyroscope to move out of the plane of the meridian and settle, in the northern hemisphere, in a plane that is east of the meridian. The amount of movement is a function of latitude and must be accordingly compensated for. A similar error exists in the pitch gyroscope as a result of the horizontal earth rate. Compensation is accomplished by computer control.

Control System Error - Control system errors involve the capability of electrical and mechanical controlling devices such as ballistics, level sensors, accelerometers and gyroscope torquers to provide instantaneous and perfect operation. This is an obviously impossible task, and as a result, a large portion of the total error budget for a precision gyrocompass is generated here. As has been discussed earlier in this report, there are many methods employed to reduce control system errors in precision gyrocompasses. One of those, for example, involves the replacement of liquid ballistics with accelerometers or level sensors.

Friction Errors - Another significant error source is undesirable gyroscope precessions caused by mechanical friction within the system. These precessions can only be reduced by improved methods of gyroscope suspension, as discussed earlier, and as the control system errors, they make up a significant portion of a specified error budget.

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Computer Truncation Error - Computer truncation is a subtle form of random error involving the word length capacity of the computer. Truncation means that all information after a certain word length is completely dropped from the system, e.g., 1.234 might be truncated at 1.23 thereby introducing a greater than 0.3 percent error. Although there are practical limitations, this type of error can be reduced by increased computer capacity.

Stepping Errors - Another source of random error which affects system resolution and ultimate precision is introduced by the common practice of using gyrocompass repeaters that provide bearing information incrementally, e.g., 1/6° steps. It is not a good practice to use step repeaters with precision gyrocompasses, as they can greatly reduce a system's precision. Rather, a continuous bearing signal from the gyrocompass should be used as a direct input to other sensors or continuously reading repeaters. It is true that mechanics and electronics for accomplishing this will contain error sources; however, these can be compensated for. Compensation for step repeater systems can only be done to the limitation imposed by the magnitude of the stepping increment.

In total, it is the residual errors that are cause for concern, since many of the error-producing factors noted above can be compensated for. Compensation involves, in most cases, a mathematical model which represents the error being compensated for. Residual errors result as actual and predicted models vary.

2.1.9 Potential Application to Buoy Tending Operations

The general navigation gyrocompasses, Sperry MK14, MK27, and MK227, installed on various Coast Guard buoy tenders are used for three primary purposes. These are: (1) general navigation, (2) input to other equipment, e.g., alidade, pelorus, radar, and (3) buoy placement. General navigation and ship maneuvering do not generally require a precise gyrocompass. Errors of one or two degrees in heading are normally acceptable. However, errors of that magnitude would become quite significant if buoy placement was accomplished by use of a gyrocompass referenced alidade, pelorus, or radar to determine bearing, especially for distant sighted landmarks, if the gyrocompass error is not adequately determined.

According to a 1977 survey conducted by the Coast Guard R&D Center, approximately 60 percent of all buoys set by the Coast Guard are set with the aid of gyrocompass bearings. Only fifteen percent are set solely with gyrocompass-based bearings and 45 percent are set using gyrocompass bearings as an input to a position solution involving other types of position lines. The use of precision gyrocompasses could possibly result in an increase in gyrocompass-based buoy placements. A more precise reference would be available for pelorus and alidade usage, although it must be pointed out that the errors associated with their use are of sufficient magnitude to possibly nullify any

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advantage provided by a more precise reference. A more positive benefit would be to other positioning sensors which require a gyrocompass input for position determination. Precision radars, laser systems, and some underwater acoustics systems are examples.

2.1.10 Safety Considerations

All of the precision gyrocompasses discussed herein have been designed to military specifications. Although well-known hazards associated with rotating machinery and electronic circuits exist, during normally conducted operations and maintenance, precision gyrocompasses do not present any unusual safety hazards.

2.1.11 Comparison of Precision Gyrocompass Systems

For comparison purposes, Table 2-1 includes a general navigation-type gyrocompass, the Sperry MK227, in a matrix of system characteristics for the several types of precision gyrocompasses which were identified in Subsection 2.1.6. One can note that the average precision gyrocompass would occupy about the same amount of space as the MK227, use slightly more power, have a somewhat lower mean-time-between-failure and offer a dynamic precision of about 4.0 minutes r.m.s. compared to approximately 45.0 minutes r.m.s. This improvement in accuracy is not without its penalty; the average precision gyrocompass costs on the order of $100,000 as compared to the acquisition cost of $19,000 for the MK227.

2.1.12 Conclusions

General navigation gyrocompasses, Sperry Marine Systems Models MK14, MK27, and MK227, are at present installed on various Coast Guard buoy tending vessels. In addition, a very small number of Sperry MK19's are in the buoy tender fleet. These gyrocompass systems, with the exception of the MK19, cannot provide the accuracy which is necessary for positioning Coast Guard aids to navigation. The MK19 and other precision gyrocompasses which have been presented in this report have the potential for that degree of accuracy when properly utilized.

The MK19 is a precision gyrocompass, as defined here, but it is becoming obsolete as new gyrocompass and computer technology advances. Both the MK29 and the AN/WSN-2, which cost about the same as the MK19, offer better potential accuracy, much smaller size and less power consumption. The MK23 is classed here as a precision gyrocompass, but is not significantly more accurate than the MK227. The Honeywell Marine Systems' SPN/GEANS is in the accuracy class of the MK29 and AN/WSN-2 and, due to its inertial makeup, is about twice as expensive and requires an external position reference for periodic updating. The ring laser gyrocompass has great potential in that it may offer instantaneous warmup, 3 minute r.m.s. precision and a comparatively low price. However, it is not fully developed and to date there has been very little terrestial testing of the system, as it is primarily being developed for aircraft inertial navigation systems.

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Approximately 60 percent of Coast Guard floating aids to navigation are set with the aid of gyrocompass-based bearings. This percentage could be increased with the installation of precision gyrocompasses on Coast Guard buoy tending vessels, if the main purpose of the installation was to provide a more precise bearing to other automatic sensors such as a precision radar. Random errors associated with the use of alidades and peloruses might preclude the possibility of obtaining sufficient survey accuracy by combining them with a precision gyrocompass. But, even here, a potential accuracy gain does exist, especially if random errors are reduced by future improvements to alidade and pelorus survey equipment and procedures.

TABLE 2-1

PRECISION GYROCOMPASS COMPARISON MATRIX

TYPE/MODEL	HEADING PRECISION (RMS) STATIC/DYNAMIC	MTBF (HR)	LIFE EXPECTANCY (YEARS)	COOLING REQUIREMENTS	START-UP TIME	VOLTAGE/ FREQUENCY/ PHASE	CALIBRATION CYCLE	OPERATING POWER (WATTS)	MAXIMUM POWER (WATTS)	UNIT COST (BASED ON PURCHASE OF 50 UNITS) ACQUISITION	MAINTENANCE SPARES	SIZE (INCHES)	WEIGHT (POUNDS)
SPERRY MK 227	.5°/.75°	3750	20	AMBIENT AIR	4 Hrs.	115 V 60/400 Hz 1φ	NONE	300	400	$19,000	$2,500[g]	15X19X50	250
SPERRY MK 23	.2°/.5°	2000	20	AMBIENT AIR	4 Hrs.	115 V 400 Hz 3φ	NONE	500	675	$36,000	$8,000	18X14X19,14X12X16 17X14X6 18X15X6	256
SPERRY MK 19	.1°/.2°	866[c]	20+	AMBIENT AIR	1 Hr.[f]	115 V 400 Hz 3φ	NONE	1190	1190	$100,000	$15,000[h]	25X25X38,25X25X4 61X23X17 31X19X13	1450
SPERRY MK 29	1.5Min./3.7Min.	2500	10+[d]	AMBIENT AIR	44Min.[f]	115 V 400 Hz 3φ	3 Mo.	225	360	$100,000	$20,000[h]	20X20X29	450
LITTON WSN-2	2.1Min./5.6Min.	3000	20[d]	AMBIENT AIR	30 Min.[f]	115 V 400 Hz 3φ	NONE	600	1200	$100,000	1	17X21X46	335
HONEYWELL ELECTRICALLY SUSPENDED GYRO SDN/GEMS	3.0Min./3.0Min.[b]	1600	10+[d]	COOLED AIR	30 Min.	115 V 400 Hz 3φ	150+ Days	400	4200	$200,000	$6,700[j] $14,100[k]	19X19X35	290
RING LASER[a] (GYRO)	3.0 Min.	2500	10+	COOLED AIR[e]	2-20Min.	115 V 400 Hz 3φ	NONE	220	220	$40,000			

[a] Not in production, all values are projected

[b] 1.5 Min. accuracy is optional

[c] 1483 Hrs. on critical items

[d] Projected

[e] Production goal is ambient air

[f] Full accuracy in 4 Hrs.

[g] Depends on what maintenance facilities are used

[h] Navy-specified spares

[i] No specified spares list

[j] Based on 40 Hrs. operation per month and 800 Hrs. maintenance interval

[k] Based on manufacturer's recommendation of 4 field labs and 1 depot

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2.2 Laser Rangefinder Methods

2.2.1 Introduction

Immediately after the announcement of the first laser in 1960, practically every company of any consequence in the electronics and aerospace industries, not to mention universities, government agencies and research foundations, plunged into laser research. Most of the work was sponsored by various American defense agencies whose initial efforts were centered upon the development of high-powered lasers for missile tracking and possible destruction. Practical applications are now in use for industry, government, the military and research of all kinds. Many additional uses in a wide variety of fields are being discovered.

One of the many applications of lasers is in distance measurement. Optical rangefinders use time-resolved methods to determine the transit time of reflected light energy, similar to radar techniques. They are generally relatively simple systems and offer high precision and high achievable accuracy. Typical accuracies obtained using pulsed lasers are on the order of a few meters at ranges of 25 kilometers or more. Greater accuracy may be obtained using CW output with frequency modulation, used to eliminate the error attributable to the delay during the rise time of the pulsed source. Light beams may be modulated with more than one frequency to eliminate ambiguity, the greatest precision being obtained at the highest modulation frequency. A retroreflector or other reflective devices/materials can be mounted on an object to increase range when measuring long distances. The phase shift of the reflected signal is compared with the reference signal reflected along a reference path of known length built into the system. Ranges of over 80 kilometers measured to an accuracy of +6mm have been obtained in this way using a frequency-modulated CW helium-neon laser (5).

In order to range greater than a few hundred meters, an optical rangefinder must be high powered or use a cooperative object (e.g., reflective material) or both. High power is of concern because of the possibility of skin or eye damage depending upon the power (power density) and the transmission wavelength. In general, low power systems are considered to be completely eye-safe at all distances from the laser and are often used by land surveyors. They generally use cooperative objects. On the other hand, high power systems are seldom eye-safe at distances less than 500 to 1000 meters from the output lens (6). Ranging to moderate distances is possible using non-cooperative objects and at longer LOS (line-of-sight) ranges using cooperative objects.

As laser surveying systems are being used for land surveying, it is perhaps reasonable to consider that they could also be used for hydrographic surveying, buoy placement or auditing. This practice is not widely used at present, but is encouraged by various manufacturers. A major drawback to using a laser rangefinder for this application is that the inherently narrow beamwidths of the transmitted beam make it difficult to maintain track of distant objects while in motion (e.g., a survey launch or a buoy tender). This drawback can be reduced by situating the device on a stabilized platform and/or by using wider beamwidths and accepting a possible lesser degree of accuracy. A more suitable application might be to situate the rangefinder on

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land at a control point and range to objects in the water. This would offer
maximum achievable accuracy at much less cost than a stabilized platform system.

2.2.2 History of Development

Development of the laser has roots in the science of thermo-
dynamics, the study of heat and its effects. In the late 1800's, scientists
were puzzled by certain aspects of the black-body radiator. Being a hollow
sphere lined with a layer of thick felt over which a uniform layer of soot or
lampblack has been deposited, the black-body absorbs all visible energy and
reflects none. Scientists introduced heat and light through a small hole in an
otherwise sealed black-body. This resulted in radiant energy being emitted at
some visible and infrared frequencies. Increasing the temperature of the heat
source not only increased the amount of radiant energy, but it also changed the
spectrum of the radiation, a phenomenon which they could not explain.

About 1900, Max Planck, a German professor, reasoned that a
lampblack molecule might be looked upon as a tiny generator which would vibrate
under the influence of heat energy. He described this energy as a product of a
constant and the frequency of radiation. His theory, which is called the
quantum theory, conceived of energy traveling in small packets.

Albert Einstein expounded on Planck's theory and named his
radiation quantum a photon. Einstein found that he could equate the energy of
an incident light ray with the energy of a reflected ray by adding the kinetic
of the liberated electrons to another quantity which he called the work
_____. He showed that there were three processes required to explain thermal
equilibrium: absorption, spontaneous emission (fluorescence), and stimulated
emission. The first two occurred naturally and the latter was not considered
important.

Neils Bohr, a Danish physicist, postulated at about this time
that atoms (he studied the hydrogen atom because of its simplicity) possessed a
number of rings or shells, about the nucleus, in which electrons orbited. He
further postulated that quantum energy resulted from orbital shifting of the
electrons between rings.

What all these distinguished gentlemen had done was describe
luminescence; light emission which cannot be considered to be caused solely by
the temperature of an emitting object. Throughout the years, the quantum theory
evolved into quantum mechanics as scientists better described Bohr's theory.
They found that the orbital shells corresponded to energy levels; the higher
the level, the higher the energy. In order for an electron to achieve a
higher level orbit, it must absorb energy. This energy could be supplied to a
molecule by bombarding it with a concentration of electrons. Once an electron
was forced to a higher state of energy, it would naturally fall to a lower
level and emit radiant energy in the form of a photon. This led to the concept
of the molecular oscillator. Upper frequency bounds, which had been limited by
the smallest size that a cavity (resonator) could be made were then seemingly
limitless, since the atom itself could conceivably be used as an oscillator.

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The first application of this concept was made by Charles Townes in 1953 (29). He concentrated a beam of excited (higher energy level) ammonia molecules and focused it through a small hole into a cavity which was tuned to 24,000 MHz. This resulted in a surplus of excited electrons inside the cavity which then caused stimulated emission of photons. The stimulated emission caused more stimulated emission in an avalanche manner and by directing the squirt of his beam into the cavity, he sustained oscillation in it at precisely 24,000 MHz. He called his invention the maser (Microwave Amplification by Stimulated Emission of Radiation) but, in fact, he had an oscillator, not an amplifier.

Over the next few years the maser oscillator was refined to the point that it became an exceedingly good high frequency amplifier. The first solid-state three-energy-level (stable, metastable, unstable) maser was developed by Nicolaas Bloembergen, a professor at Harvard. His device would not amplify; however, James Mayer, Lincoln laboratory, improved the solid-state maser and made it amplify. His device and those that followed allowed microwave amplification at levels never before attainable. Among other applications, the maser amplifier was applied to radio telescopes, allowing radio astronomers to listen in on microwave emissions from distant galaxies.

Charles Townes, in an effort to bridge the frequency gap between microwaves and light waves, decided in about 1957 to attempt amplification at visible light and work back from there (29). He conceived of a set of parallel mirrors with a collection of excited atoms reflecting back and forth between them. He reasoned that if the total amount of light emitted by the photons was greater than the reflection losses, the light would gain in intensity. His theory was realized in 1960 when Theodore Maiman, Hughes Research Laboratories, produced the first optical maser (29), or "laser" as it became to be known (Light Amplification by Stimulated Emission of Radiation). Maiman's device consisted of a ruby crystal irradiated by a xenon flash lamp, producing a needle-thin, pulsed red light of high intensity.

Since Maiman's discovery, lasers have been developed that operate from the infrared through the visible and into the ultraviolet spectrum. They are of low power, high power, continuous wave and pulsed at high or low repetition rates. They are being applied to practices as diverse as "spot welding" of retinas (which have become detached from the choroid) and measuring the distance to the moon (using the optical reflectors placed there by astronaut Neil Armstrong).

2.2.3 Characteristics of Laser Light

For some users, the beam from a laser is superior to light from a more conventional source in four respects: intensity, directivity, coherence, and monochromaticity.

Intensity - Although the total energy in the pulse from a laser is not very great, it is highly concentrated in time and direction. Each photon is in phase with the rest of photons in the beam and the amplitude of the beam is increased as much as possible.

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In a light bulb, the individual atoms release their electro-magnetic energy randomly in time. If this light is focused on a steel plate, for example, an irregular stream of photons will hit the plate one after another not at precisely the same spot but over a relatively large area. The energy is spread over too long a time and area to have much effect. On the other hand, a laser beam is so narrow and intense that several million photons strike a tiny point on the steel almost simultaneously.

Directivity - When light emerges from a laser, it does not diverge (spread) very much at all. Thus, the energy is not greatly dissipated as the beam travels. A typical Helium-Neon laser has a rated beam divergence of 0.5-1.5 milliradians (about 1-1/2 to 4-1/2 minutes of arc).

Directivity of the laser beam is controlled by the mirrors at the end of the optical cavity (which in the case of the ruby laser is the ruby crystal itself). Only when the beam originates parallel with the cavity axis will the mirrors keep it inside the cavity long enough to produce directivity as well as amplification.

Coherence - The term coherence, as used here, means that separate light waves in the beam are exactly in step with one another, i.e., they have the same phase. Laser light is coherent because stimulated emission always produces a photon that is in phase with the original light beam. The quality of coherence is important because it allows observation of the inter-ference effects that occur when two or more wave trains from different directions overlap and interact. This phenomenon has many technological applications that could not be exploited until the advent of the laser.

Bandwidth - The last special characteristic of laser light compared to conventional light is its monochromaticity. All conventional light sources produce light of more than one wavelength, however, light from certain kinds of lasers is much more uniform in its wavelength content. The narrow spread of wavelengths in the laser beam, like its intensity and coherence, results from the special nature of the generating process. Energy-level charac-teristics of the chromium atom in ruby, for example, cause an incident photon to stimulate another photon of the same wavelength much more readily than one of a slightly different wavelength. This one wavelength from the band of possible wavelengths is built up to the exclusion of others.

2.2.4 Laser Light Transmission Technique

In practice, photons from laser transitions are emitted in all directions from a rod of laser material, preventing a cumulative buildup of emissions. The necessary cumulative buildup is achieved by placing mirrors at each end of the rod. One of the mirrors is essentially totally reflecting and the other is partially reflecting so that a portion of the incident light is transmitted. The mirrors, perpendicular to the optical axis of the rod, cause a buildup of the light emitted along the axis. A positive feedback results so that a rapid accumulation of radiation occurs. Because this feedback only occurs along the axis of the laser material, the light is not radiated in all directions; instead, it is directed along the axis and emerges from the partially reflective end as a very narrow low divergence beam. This low divergence is an

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important characteristic in that it allows for higher beam density which results in signals which can be readily detected over long distances, giving rise to such applications as surveying and rangefinding, using electronic distance measuring (EDM) equipment.

2.2.5 Laser Types

Lasers can be classified according to the state of their laser material. Four common families are presently recognized:

Solid-state lasers employ laser material distributed in a solid matrix. One example is the ruby laser which uses a precise amount of chromium impurity distributed uniformly in a rod of crystalline aluminum oxide. The output is primarily at wavelength 0.6943 um, which is deep red in color. Another example is the Nd:YAG (Neodymium:Yttrium Aluminum Garnet) laser which is commonly used in long range electronic distance measuring (EDM).

Gas lasers use a gas or gas mixture within a glass tube. Common gas lasers include the He-Ne laser at 0.6328 um and the CO_2 laser at 10.6 um in the infrared region. Argon and krypton lasers, with outputs in the green and blue regions, are becoming quite popular.

Liquid lasers, which are relatively new, usually use a complex organic dye laser material. The most striking feature of the liquid lasers is their "tuneability." Proper choice of dye and its concentration allows light production at almost any wavelength in or near the visible spectrum.

Semiconductor lasers are not to be confused with solid-state lasers. Semiconductor devices consist of two layers of semiconductor material sandwiched together, e.g., gallium-arsenide. One element contains an excess of electrons and the other has a deficiency of electrons. Two outstanding characteristics of the semiconductor laser are its high efficiency and small size. Typical semiconductor lasers produce light in the red and infrared regions.

The majority of optical EDM devices being manufactured for surveying operations are of two specific types:

Gallium-Arsenide Diode - Although the Gallium-Arsenide (GaAs) alloy can be used in a laser, it is generally used in optical rangefinders as the doping agent for a LED (Light Emitting Diode). The CW output is incoherent light generally at the infrared wavelength of 0.91 um. Since it is incoherent, special processing is required to develop the narrow, low divergence beam and reduce range errors which are due to small differences in time measure of the transmission and reception of "out-of-step" light wave fronts. These errors generally amount to a few millimeters. The LED EDM device generally transmits very low power (on the order of micro-watts). This restricts the range capability of such devices to one or two miles, requires the use of reflective surfaces to return the transmitted signals, and dictates the need for highly sensitive detectors. Among the advantages of the LED rangefinder are simplicity, relatively small size, low power consumption, and very importantly, it is eye safe at all distances from the transmitting window.

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Helium-Neon Gaseous Laser - HeNe laser EDM's offer better precision (millimeters) and longer range capabilities than the GaAs LED. Greater accuracy results from the spatial coherence of laser light and greater range results from the higher transmitted power (vicinity of 1-3 mW). HeNe EDM's can range over short distances to low reflectivity surfaces such as reflectorized highway signs. One to three kilometers range may be obtained using a simple plastic reflector. By using a combination of optical retro-reflectors, ranges in excess of 60 kilometers are obtainable. This class of rangefinders is larger in size and requires more power than the GaAs LED EDM's. Although larger in size, they are still portable, weighing around 40 pounds, more or less, and having a volume of 1-2 cubic feet. Whereas the GaAs variety most often incorporates a small rechargeable Nickel-Cadmium battery pack, HeNe EDM's generally operate from standard 12 VDC storage batteries.

The higher power level of the HeNe laser EDM presents a degree of eye hazard. One must not stare into its beam. The degree of hazard increases with power density (function of beamwidth and accessible radiant power) and exposure time. Manufacturers are required (7) to affix appropriate caution labels to the cases of HeNe lasers when the CW power is between 1 and 5 mW. In addition, certain other safety features must be incorporated, such as a key lock on the laser.

Although not applied to general land surveying, high power pulsed lasers such as ruby and Neodymium-YAG are also used for distance measuring. This class of lasers presents a definite eye hazard up to several hundred meters from the transmitter. They are generally used in the military environments or wherever maximum personnel safety is afforded. The precision is less than those mentioned above (on the order of $\pm 5m$) because of less precise time measurement techniques associated with pulse type signals. The principal advantage of the high-powered EDM's is that less sensitive detection networks are required. Ranging to passive objects (poor optical reflectors) at several kilometers is possible.

2.2.6 Light Wave Detection

The detection of light waves is commonly done with the use of photomultipliers or photodiodes. The photomultiplier operates on the principle of secondary emission being larger than incident radiant energy. Secondary emission electrons are bounced between plates of photosensitive material until a sufficient energy level is achieved for electronic processing. Photodiodes operate on the reverse principle of light emitting diodes, taking advantages of p-n junction diode characteristics.

2.2.7 Rangefinder Operating Principles

Phase-shift measurements are made by using the amplitude modulation of a light beam. The wavelength of the modulation envelope is chosen to be consistent with the requirement of the measurement (e.g., length of measurement).

The modulated light is transmitted through a transmitter optics assembly and projected towards the point of measurement where a retro-reflector sends the beam back to the instrument. A receiver optics assembly

focuses the beam on a photodiode detector/mixer, which produces an electrical signal that has the characteristics of the received modulated light envelope. Ideally this signal is identical to the modulation signal except for a displacement or phase shift proportional to the path length.

The phase shift between the transmitted and received signals is a consequence of the finite velocity of the signal envelope, which is essentially equal to the speed of light. Typically, phase measurements of the signals can not distinguish between zero and 360 degrees phase shift, thus leading to repetitive phase-versus-distance characteristics. To resolve the ambiguity, more than one modulating frequency is used; a lower frequency for gross range and higher frequencies for precision (e.g., 75kHz provides 2000-m measurement intervals and 15 MHz provides 10-m intervals).

In the idealized amplitude modulation system, the output signal of the detector is compared with the signal driving the modulator to determine phase shift. In practice, modulators and detectors introduce phase shifts. If these phase shifts were constant, they could be taken into account in the measurement. However, they can vary considerably with time and temperature and can therefore introduce measurement errors. One solution to the problem is to generate a reference signal that has been exposed to the same variable phase shifts (except that which is proportional to the distance being measured) as the transmitted/received signal. This is accomplished by alternately directing the output of the amplitude modulator to the transmitter optics and through an internal reference path to the detector. This guarantees that any phase shift introduced by the modulator and detector is present in both the external signal and the internal reference, so any difference in phase shift between these two signals is proportional to the distance being measured.

The basic precision and achievable accuracy of the EDM is determined by the accuracy and stability of an internal oscillator in the transmitter. In a GaAs rangefinder system, the transmitter provides the drive signal to the emitting diode. It divides the oscillator frequency to provide additional modulating frequencies and the reference frequency. The transmitter also provides the necessary frequencies to the receiver.

The transmitter diode produces a modulated light beam under the control of the transmitter drive signal. A chopper, a blade rotating at a 10-Hz rate, alternately routes the diode output either through the transmitter optics or through the reference path which contains a variable optical attenuator. The radiant output from the LED originates at the focal point of an optical assembly that forms the beam and projects it.

The receiver and a phase-lock circuit provide the local oscillator drive to the photodiode detector. The local oscillator drive is always the reference frequency above the modulation frequency being transmitted. The receiver filters the detector output to eliminate all but the reference frequency.

The limiter takes the reference sine wave and produces a square wave output. Under control of a microprocessor, the limiter detects the difference between the external path signal amplitude and the internal path

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signal amplitude and resolves this difference with the variable attenuator. Data collected by the phase detector during the level balancing moments are questionable and are therefore discarded.

The phase detector and accumulator circuit determines the distance by measuring the phase difference between the reference signal and the square wave output which was produced in the limiter. The internal path is measured first. An accumulator is counted upward by the highest resolution modulating frequency for several cycles (typically 100) of the reference signal. Other modulating frequencies will be counted in a like manner, but generally for fewer counts (e.g., 10). The accumulator holds a number that represents the average phase difference between the reference signal square wave (internal path). The process is repeated for the external path except that the counter is counted down. The accumulator then holds the average difference over 100 cycles between the external and internal paths. Measured data are then transferred to the microprocessor for analysis and display.

Operation of a HeNe laser rangefinder is very much similar, with the transmitting optics, the source excitation and modulation methods being the major differences. The light source is a HeNe mixture which is contained in a sealed tube. Excitation of the helium is accomplished by discharge of electricity through the tube, similar to a neon sign. The mirrors may be enclosed in the tube, form the end caps of the tube, or since the alignment of the mirrors is a delicate operation, they may be mounted separate from the tube. When the latter is done, the laser tube ends are made from pyrex or quartz set at a prescribed angle to the axis of the laser, and the output light is polarized. Modulation is generally done with a Pockels cell, a device containing an electro-optical crystal and utilizing the Pockels effect. This is a linear effect found in particular crystals that are capable of advancing or retarding the phase of the induced ordinary ray, relative to the extraordinary ray when an electric field is applied. Because the effect is linear, retardation is directly proportional to the intensity of the applied electric field.

2.2.8 Rangefinder Operating Procedures

Operating procedures for optical rangefinders are generally quite simple and require little training. After an initial setup, the operator merely pushes a button and waits a few seconds for the measured range to be displayed digitally. The initial setup and measurements for establishing the position of the rangefinder might include the following:

Transportation and Unpacking - Carrying cases for the range-finder and accessories are available. The entire surveying system is easily transported by two people.

Locate Control Points - Control points for reference and for rangefinder position, such as Coast and Geodetic Service survey points, could be used for initial reference. Of course, any point may be used for relative position work.

Place Rangefinder's Mounting Tripod - Center of tripod must be placed over the control point and rough leveling accomplished. In some cases,

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a plumb may be used for centering; in other cases a downward-looking telescope with centering marks may be used. Leveling may be done with an installed "bull's-eye" level or other similar methods.

Mount Rangefinder - In most applications a tribrach is used to adapt the rangefinder's mounting hardware to the tripod.

Provide Power - In many cases rechargeable battery packs are available and the operator need only attach the interconnecting cable to the rangefinder. Almost all of the rangefinders operate from 12 VDC and may be connected to a standard storage battery. A separate cable is generally supplied for this purpose.

Choose Objects - In most cases optical retroreflectors are used as the objects. However, as previously discussed, it is sometimes possible to range on reflectorized surfaces or plastic reflectors and in the case of high power systems ranging may be done passively to any object. Optical retro-reflectors are mounted on a tripod similar to the rangefinder mounting. Of course, they may be permanently mounted.

Calculate and Compensate for Environmental Factors - A correction has to be applied to the rangefinder to account for variations in the speed of light due to temperature and pressure. A correction factor expressed in parts per million (ppm) is determined by entering a chart or circular ppm correction guide with the measured temperature and pressure. In many cases this factor may be directly entered by using controls on the rangefinder. The measured ranges will then be automatically compensated. In other cases the measured reading must be adjusted accordingly. For short distance measurements, the environmental readings at the location of the rangefinder should be sufficient for proper correction. At long distances and/or across different terrain (e.g., warm land/cold water), it would be advisable to measure the environment at the end points plus a few other spots in between and average all readings to determine the correction factor. The operator should determine the relative merits of such an exercise by weighing his precision requirements against the fact that the full correction range is typically +100 to -100 ppm.

Measure Distance - Adjust horizontal and vertical tangent screws to precisely center beam on an object after rough pointing has been accomplished. Precise pointing might be indicated simply by the display of a range reading, maximum return of a visible light wave or most commonly by a meter indication. Adjust pointing and, if necessary, an optical attenuator until the signal is peaked within a certain scale on the meter. When a choice is available, select the desired measurement, e.g., horizontal, vertical, or slant range. Push the button to start the measurement process.

Read Vertical Angle - Read the vertical angle with respect to the local level. In some models the vertical angle is internally processed to develop horizontal range and vertical height difference between the rangefinder and the target. In other models the calculations are made manually (hand-held calculator for example).

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Record Data - Record all pertinent data so that position determination from range measurements can be made.

Disassemble, Store and Recharge Batteries - Not a lot of storage space is required for an average optical rangefinder system, although the tripods are a bit unhandy due to length as compared with the other system components. Nickel-Cadmium batteries are rechargeable overnight.

2.2.9 Accuracy Considerations

Accuracy considerations will be lightly treated here as the advertised accuracy for short to medium range CW optical rangefinders is on the order of one or two magnitudes greater than that which is required for positioning buoys.

As in many different types of systems, operator mistakes are potentially the greatest error source when using laser rangefinders. However, the procedure for using laser rangefinders do not allow much latitude for operator error. In order for most rangefinders to obtain range data, the laser beam must be precisely pointed at a reflector before sufficient return signal strength is obtained for processing. The laser beam divergence is very narrow and only at long distances is the beam diameter sufficiently large to allow a significant pointing error. Range data are displayed digitally in all systems, reducing the possibility of operator mistakes in reading the ranges.

Random errors are largely comprised of the rangefinder's time base errors, propagation errors, and calibration errors. Since the time base is the heart of the rangefinder, manufacturers install oscillators (generally quartz) that exhibit good short term stability with long-term stability being on the order of a few ppm/year. Errors in propagation are caused by atmospheric refraction of the light carrier. A ppm correction control is usually provided to compensate for these errors which are predominantly a function of atmospheric pressure and air temperature variations.

A potential systematic error source is prism offsets which are a function of a prism's point source and the orientation of its holder mechanism. For example, the point source may be behind the vertical axis of the holder, which in many cases describes the axis for centering over the reference mark. Some manufacturers provide prisms with zero offset; others vary. Compensation for the offset in the rangefinder is sometimes done by hardwire or by means of an adjustable offset control. The operator must be aware of the prism offset and the means available for compensation, even if that may be by manual correction to the displayed range.

Probably the largest single error potential is in miscalibration. Calibration of a rangefinder only (no theodolite base) is a relatively easy procedure. This type of calibration is exclusively done by comparison to a known calibrated path length. A check against a calibrated path length is recommended prior to every mission. A log of the calibration readings would serve as indication of deterioration. Any observed offset would be used to correct the displayed readings either manually or electrically.

High-powered pulsed laser rangefinders possess an additional error source. Time/distance measurement accuracy is limited by electronic ability to precisely perform pulse edge measurements. Differing from CW type phase measuring techniques, this is the principal reason that pulse-type laser rangefinders have advertised accuracies which are usually specified as within a few meters, while CW types have advertised accuracies specified as within millimeters.

An application error source is apparent when measuring in a non-static mode, as when the object or measuring platform is in motion along the line between the rangefinder and the object. An example would be a buoy tender pitching and rolling due to wave activity. Even a stabilized platform would not be able to compensate for this type of range variation.

A more exhaustive error analysis would be in order for a major laser system such as a laser radar or computer-based, semi-automatic system proposed above. However, since it is only a proposed system, no attempt will be made to analyze the error sources here.

2.2.10 Potential Application To Buoy Tending Operations

As previously noted, application of optical rangefinders to hydrographic surveying is not widely practiced, and informal inquiries have not uncovered anyone using them to set an object, e.g., a buoy, in water. However, this is a prospect for not only setting a buoy, but also for auditing its position at times after the initial setting. The latter application is more promising if used in an area from which many aids can be seen from a few locations and good horizontal control is available. Given control points above the surrounding terrain, three relatively high-powered laser rangefinders, buoys with the appropriate reflective surfaces and three operators with radio communications, it would be feasible to audit the position of a large number of buoys in only a few hours (from base to the field and back to the base). Data reduction could be done in the field or at the base.

Using optical rangefinders as surveying instruments to set buoys is a bit more complicated. The complication arises mainly in dynamic operation. If the rangefinder(s) were aboard a buoy tender, the operators would experience considerable difficulty in keeping the narrow light beam on target while the tender pitches and rolls in the water. This difficulty could be lessened by the installation of expensive stabilized platforms to eliminate pitch and roll. An alternate method might be to place several reflectors on the ship and plot its position using rangefinders placed on shore. The logistics of this method would limit its application, but tracking in this manner is easier.

Let us for a moment consider a system which incorporates three (for example) laser rangefinders in a computer-based semi-automatic operation (9). An operator, aided by visual and electrical sensors, could direct the rangefinders onto reflectors at reference stations with joy sticks which control steerable mirrors mounted in stabilized platforms. Once acquisition was made, the system would be placed in automatic track and a continuous position readout provided by computer-controlled coordinates. The readout

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would be in the same reference system (NAD27) as that of the reference stations coordinates. Difference angles could be used for additional fix confidence. Total error for such a system could be less than one meter. Range would be dependent on the power of the system chosen. The best laser choice would probably be a CO_2 type. This class is newly developing and has the feature of good haze, fog, moisture, and dust penetration at the operating wavelength of 10.6 um. The acquisition cost is estimated to be $150,000, with the major portion being the stabilized mirror box platforms at about $30,000 each.

There are many applications of laser trackers and rangefinders in the military. Applications vary from armament projectile tracking to a handheld monocular rangefinder used in troop combat situations. Technology is well advanced so that adapting a system for buoy tending would merely require the application of existing knowledge and hardware, albeit at considerable expense.

2.2.11 Safety Considerations

The majority of optical rangefinders are one of three classes: low-power, short-range GaAs LED; low to medium-power, short to medium-range HeNe laser; and high-power, long-range NdYAG. The safety spectrum covered by these devices spans from completely eye and skin safe for the GaAs LED to hazardous for high-powered NdYAG lasers. Varying MPE (maximum permissible exposure) levels, which are a function of power density of the light beam, wavelength of the radiation and exposure time, have been set by different government agencies, including the U.S. Army and U.S. Air Force. Various industry standards also exist, but probably the most widely followed standards are those suggested by American National Standards Institute, Inc. (7). These standards provide reasonable and adequate guides for the safe use of lasers with output wavelengths between 0.2 um and 10 um.

Lasers and laser systems are classified according to relative hazards and appropriate precautions/controls are suggested for each class. The basis of the classification scheme is the ability of direct or indirect laser light to cause physical damage to the skin or eye. The four classifications are:

Class I - Exempt from control, MPE not applicable;

Class II - Low-power visible lasers and laser systems (0.4 to 0.7 um), CW or pulsed, not exceeding 1 mW for CW, not exceeding MPE for a 0.25 second exposure for pulsed;

Class III - Medium power lasers and laser system, infrared (1.4 um to 10 um) and ultraviolet (0.2 to 0.4 um), can exceed MPE but cannot exceed 0.5 W for more than 0.25 seconds, visible (0.4 to 0.7 um), CW or pulsed producing excessive radiant power for a 0.25 second exposure (1 mW for CW) and average radiant power less the 0.5 W (1 to 5 mW for CW), Visible and near infrared (0.4 to 1.4 um), single-pulsed, exceeds MPE but can not exceed radiant exposure of

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10 Joules/cm^2, near infrared (0.7 to 1.4 um), CW or single-pulsed, MPE possible but can not exceed 0.5 W for 0.25 seconds;

Class IIIa - All Class III lasers having an accessible output power of from 1 to 5 times the appropriate Class III limits but does not exceed MPE as measured over a limiting aperture;

Class IV - High power lasers and laser systems - all lasers that exceed maximum values for the various Class III categories.

Control measures are non-existent for Class I, require a warning/caution label for Class II and are too numerous to fully discuss here for Classes III and IV. Some of the Class III controls concern warning labels, special education and training, special engineering controls, e.g., key start, authorized operating personnel only, special viewing procedures, etc. In addition to Class III controls, Class IV controls include use only in a controlled area, remote operation whenever possible, control of the beam path, etc.

2.2.12 Example Rangefinder Characteristics

Table 2-2 provides some characteristics of several laser rangefinders. Three companies are represented there. They were chosen because of the availability of their product information and the cross section of portable laser rangefinders systems that they are marketing. The selected equipments cover the range of less than a kilometer to sixty kilometers, offer various light sources and power levels and are straight rangefinders or rangefinders with attachable or incorporated theodolite bases. System acquisition prices range from about $9,000 to more than $30,000.

2.2.13 Conclusions

In general, laser (light carrier) rangefinders can provide accuracies superior to that which is necessary to properly position Coast Guard aids to navigation. According to manufacturer literature, short-range, phase-modulated systems can provide range accuracy specified in units of millimeters. Long-range, pulsed systems are capable of a range accuracy specified at five meters plus a few parts-per-million.

In addition to precision and potential accuracy, there are several additional advantageous characteristics of laser rangefinders. There are a wide variety of laser rangefinder survey systems on the shelf commercially. These systems are generally easily transportable and simple to set up and operate. No special training is necessary for the operator beyond familiarization with the operator's manual. The systems are easily tied to a geodetic reference system (e.g., State Plane Coordinate System) simply by locating the receiver/transmitter or reflector over a previously surveyed (and validated) site. For operation in poor visibility situations, a rangefinder with a visible light carrier could be used to facilitate locking on and/or tracking a reflector.

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Although not necessarily disqualifying, there are certain factors that limit the operation of laser systems for buoy-tending operation:

(1) Their inherently narrow beamwidths, which are advantageous to multipath reduction and increased signal-to-noise ratios, work as a disadvantage in training on a small object at a remote location. This is especially true if relative movement exists between the target and the rangefinder.

(2) Oscillatory motion of the rangefinder or reflector along the line-of-site (LOS) between them, as with ship motion, could introduce a range measurement error.

(3) Good ambient light and atmospheric conditions are essential to laser rangefinder operations. Degradation in the condition of either would result in reduced range and/or system accuracy. For this reason, laser rangefinder systems are considered to be fair weather systems only.

(4) Low-power short-range systems do not present an ocular safety hazard, but longer range, higher powered systems could, necessitating special safety precautions.

(5) If a Coast Guard calibration facility were not available, certain periodic calibration procedures might require that a particular commercial rangefinder system be returned to the manufacturer for that purpose. This is especially true for systems that incorporate a theodolite base.

In many buoy-tending situations for which a laser rangefinder could be used for positioning, theodolites and sextants could also be used. In that situation, the only advantage to be offered by the rangefinder would be another line-of-position (LOP). However, that LOP could have a high degree of precision.

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TABLE 2-2

LASER RANGEFINDERS CHARACTERISTICS*
(1 of 2)

MODEL	SLANT RANGE (km)	ACCURACY	RESOLUTION	LIGHT SOURCE	OUTPUT POWER	THEODOLITE BASE	ACCURACY	RESOLUTION
AGA CORPORATION MODEL 12	2.5	6.0 mm + 10 ppm m.s.e. (67%)	0.3 mm	GaAs LED (0.91 um)	less than 50 uW	optional	-	-
AGA CORPORATION MODEL 78	10.0	9.0 mm + 1 ppm m.s.e. (67%)	3.0 mm	HeNe Laser (0.6328 um)	0.8 mW	none	-	-
HEWLETT-PACKARD MODEL 3810A	1.6	5.0 mm + 10 ppm m.s.e. (67%)	1.0 mm	GaAs LED (0.91 um)	7-10 uW	incorporated	+40 secs. m.s.e. (67%)	1 sec.
HEWLETT-PACKARD MODEL 3820A	5.0	5.0 mm + 5mm/km m.s.e. (67%)	1.0 mm	GaAs Laser (0.830 um)	60 uW	incorporated	+10 secs. m.s.e. (67%)	1 sec.
KEUFFEL AND ESSER COMPANY RANGEMASTER II	60.0	6.0 mm + 1 ppm 95%	1.0 mm	HeNe Laser (0.6328 um)	2.2 mW	none	-	-
KEUFFEL AND ESSER COMPANY RANGER IV	12.5	6.0 mm + 2 ppm 95%	3.0 mm	HeNe Laser (0.6328 um)	2.2 mW	none	-	-
KEUFFEL AND ESSER COMPANY VECTRON DIGITAL SURVEYOR	1.6	6.0 mm + 6 ppm 95%	3.0 mm	GaAs LED (0.91 um)	60 uW	incorporated	+4.5 secs. 95%	3 secs.

*Includes Light Emitting Diodes (LED's) in addition to lasers

TABLE 2-2

LASER RANGEFINDERS CHARACTERISTICS
(2 of 2)

MODEL	SIZE OF RANGEFINDER-THEODOLITE				SUPPLY POWER	TRAINING AVAILABLE	COST**
	WIDTH	LENGTH	HEIGHT	WEIGHT			
AGA CORPORATION MODEL 12	19 cm	22 cm	8 cm	14 kg	6.0 VDC (battery)	Short operator's course at manufacturer's site	$10,000
AGA CORPORATION MODEL 78	29 cm	14 cm	19 cm	40 kg	12 VDC (battery or conventional)	Short operator's course available at manufacturer's site	$10,000
HEWLETT-PACKARD MODEL 3810A	26 cm	33 cm	15 cm	58 kg	12 VDC (battery or conventional)	Both operator's and maintenance courses at manufacturer's site	$11,000
HEWLETT-PACKARD MODEL 3820A	17 cm	24 cm	34 cm	52 kg	3.6 VDC (battery)	Both operator's and maintenance courses at manufacturer's site	$19,000
KEUFFEL AND ESSER COMPANY RANGEMASTER II	32 cm	43 cm	23 cm	88 kg	12 VDC (battery)	Both operator's and maintenance courses at manufacturer's site	$31,000 less GSA discount
KEUFFEL AND ESSER COMPANY RANGER IV	43 cm	32 cm	23 cm	79 kg	12 VDC (battery)	Both operator's and maintenance courses at manufacturer's site	$13,000 less GSA discount
KEUFFEL AND ESSER COMPANY VECTRON DIGITAL SURVEYOR	14 cm	22 cm	29 cm	41 kg	12 VDC (battery)	Both operator's and maintenance courses at manufacturer's site	$19,000 less GSA discount

**Estimated cost including necessary accessories for a field survey set-up

2.3 Inertial Guidance Methods

2.3.1 Introduction

Until the advent of radio, pilotage and dead reckoning were
the most common methods of navigation in use. With the advancement of radio
techniques, positioning systems such as Loran, Shoran, Decca, etc., were
developed to aid the navigator. Radio positioning techniques were further
advanced to satisfy faster and more accurate navigational requirements brought
about by the airplane. However, radio systems are somewhat limited since they
require extensive networks of ground stations and the equipments are subject to
both man-made and natural interference.

In recent years, improvements in gyroscopes and accelerometers
have made it possible to design and fabricate navigational systems that are
completely self-contained and require neither visual nor radio links to deter-
mine position. These systems are called inertial navigators since they make
use of the laws of motion as described by Newton 300 years ago.

A common type of inertial navigation system (INS) uses pre-
cision computer-controlled gyroscopes to provide a reference table for sensitive
accelerometers. Minute changes in velocity (accelerations) sensed by the
accelerometers are applied to a computer which may calculate velocity, direction
and other desirable navigation factors.

Developments over the past several years have produced
inertial navigation systems with good performance, size and weight character-
istics. Reliable equipments are now available to accurately measure speed in
the presence of influential environmental factors, such as wind and wave motion.
They do not necessarily require radiation from distant stations and do not emit
RF energy. If an INS is energized (if it is running), it will continue to do
its job regardless of external conditions.

2.3.2 Inertial Navigation Concepts

A body at rest tends to remain at rest, and a body in motion
tends to remain in uniform linear motion unless acted upon by an external
force - this is the crux of Newtonian physics. It is also the foundation for
inertial navigation. This original foundation as conceived by Sir Isaac Newton,
has in it a fault, however. His use of the term "at rest" eventually came
under heavy criticism. Einstein's theory of relativity shattered the premise
of "absolute motion." His view was that nothing is at rest; only sharing a
velocity with some other object and its coordinate system.

The primary measuring device in an inertial navigation system,
the accelerometer, bears out Einstein's theory. It makes no distinction between
"at rest" and any other fixed velocity (because there is none). On the other
hand, the accelerometer makes distinction between fixed velocities and those we
like to think of as fixed, but which are only fixed speeds along curved paths
(all paths are curved, inertially speaking).

Velocity is a vector quantity made up of speed and direction. It is a description of a state of motion; a time-rate-of-change of position. If direction is changing, velocity is changing.

A change of velocity is an acceleration; a time-rate-of-change of velocity. A body accelerates when, and only when, an external force acts upon it.

It is the nature of matter to tend to preserve its existing state of motion. In other words, it resists changes in its state of motion. This property is known as inertia. The magnitude of the inertial force displayed by a body is proportional to the magnitude of the external force. Acceleration rate is likewise proportional, and therefore, rate of acceleration is proportional to inertial magnitude. Measurement of inertial force yields the rate of acceleration.

The development of an inertial system is based primarily in Newton's Second Law which states that the acceleration of a body is directly proportional to the force acting on the body and is inversely proportional to the mass of the body. A bit of transposing produces the familiar equation: F=ma or mg (g=gravitational acceleration). Displacement is calculated from sensed acceleration by the application of basic calculus. Velocity is the first integral of acceleration with respect to time and displacement is the second integral (or the first integral of velocity).

2.3.3 The Accelerometer

Accelerometers are devices which measure acceleration. They come in a large variety of shapes and sizes and range from simple mechanical devices to highly sophisticated electro-mechanical precision instruments costing several thousand dollars each. However, they all work on the same basic principle of measuring the inertial "pushing back" of a known mass in response to externally supplied forces.

The accelerometer is made up of two primary mechanical parts; a case and a mass. The mass is suspended within the case in a manner which permits some amount of restricted movement between the two parts. The mass has a neutral or null position where it is positioned when the accelerometer is not accelerating. When an external force acts upon the accelerometer, the case tends to react directly and move ahead of the internal mass. The force that accelerates the mass is provided by the mechanics or electronics of the accelerometer. When a state of balance is reached between this force and the inertial force on the mass, a specific displacement will exist between the case and the mass. This distance will be proportional to the acceleration of the mass, its case and any other vehicle to which the case is attached.

The relative movement of the mass is generally so small that it can only be detected by electrical pick-offs. Inductive pick-offs are common. Two coils are spaced on either side of the null position. Excitation in either coil is of the same frequency and amplitude as the other (with same amount of movement), but a phase reversal allows direction sense.

The accelerometer output can be amplified and used as an input to a phase-sensitive demodulator which produces an output that is a ±DC voltage proportional to the acceleration. This information can be used by a computer to determine velocity and distance travelled with respect to the sensitive axis of the accelerometer.

A single-axis accelerometer can only measure accelerations that parallel its input axis. In that respect, an accelerometer has no sense of direction (just forward and backward). In order to get around this, a second accelerometer, which is perpendicular to the first, can be used. This allows vector analysis of orthogonal components to establish true direction and magnitude of externally applied forces in the plane defined by the two axes. Perpendicularity of the two accelerometers is common but not necessary as long as the angular relationship is known. Defining motion in one in terms of the other is a vector algebra process known as coordinate transformation and is well within computer capability.

2.3.4 The Gyroscope

An inertial navigation system requires a device which either remains angularly fixed in inertial space or precesses in space at a known rate. Only with the aid of such a device can a stable reference base be maintained from which the accelerometer outputs can be measured as components of acceleration. The device which provides this stable reference is the gyro(scope). A gyro may be defined as a spinning mass, usually a wheel or disk, turning about an axis and supported by a system which allows the wheel to turn about one or two perpendicular axes when an external force is applied. Like its inertial partner, the accelerometer, the gyro is made up of two primary parts; the rotor (inertial mass) and a case. The rotor, which possesses angular stability, is attached to the case with a gimbal system, a method of mounting which allows total angular independence between the rotor and case.

The response of the gyro is categorized by a pair of gyro characteristics, rigidity (inertial mass) and precession. Rigidity may be defined as that characteristic whereby the axis about which a wheel turns tends to maintain a fixed direction in inertial space. The gyro physically resists torques tending to realign its spin axis. Precession is a response characteristic. To precess means to go before. If a downward force were exhibited along the rim of the spinning mass, the greatest amount of downward movement of the mass would appear at a point which is 90 degrees ahead (in the direction of spin) of the point of application (hence the concept of to go before).

2.3.5 The Stable Element

With the gyro case mounted to the same base as the accelerometers, angular movement of the accelerometers will be directly reflected by angular movement between the gyro case and rotor. Whenever the rotor is spinning and inertially stable, case movement around the rotor is indicative of any inertial instability of the accelerometers. Detection of the instability can be accomplished by using pick-off coils. By use of a closed loop servo system, this detected instability can be used to drive the accelerometers back into angular stability.

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Three accelerometers and a pair of two-degree-of-freedom gyros (gimballed in two perpendicular directions) all on a common mounting base, are basic ingredients for the "stable element." The accelerometers are oriented with their sensitive axes mutually perpendicular, e.g., X,Y and Z axes of the cartesian coordinate system. The gyros have two sensitive axes, e.g., X&Z and Y&Z. One of the Z axes is redundant and can, therefore, be used for platform corrections (to be discussed later).

In addition to the gyros and accelerometers, pick-off coils and gyro torquers are parts of the stable element. Pick-off coils were discussed previously. The gyro torquers produce a magnetic field when supplied with DC current. This magnetic field reacts with case-mounted permanent magnets to create a torquing force on the gyro rotor. These controls are mounted on axes 90 degrees apart from the axes for which they are named, conforming to the previously discussed gyro precession. Their function is to eliminate undesired precessions of the gyro which result from gyro drift caused by, among other things, the mechanical friction forces acting on the rotor. This method of counter-torquing is called gyro biasing.

The three-axes platform has all the attributes of an unobtainable three-axes gyro. If its gryos are properly biased, the stable element can be placed in any given orientation relative to a selected reference system and it will stay there. It thus becomes an inertial reference system against which to gauge angular and translatory movement of a vehicle. Mounting to a vehicle requires a platform gimbal system, a three-axes swivel which produces total angular independence between the vehicle and the reference system.

2.3.6 The Platform

The platforms of all INS contain at least three gimbals and sometimes four or five. A three-gimbal system is required to provide complete freedom of movement of the stable element with respect to the vehicle. In most platforms, the gimbals are named according to the axis that they isolate, e.g., roll, pitch and azimuth. Each gimbal axis will have an angular pick-off device (synchro) associated with it so that angles between the vehicle and the reference system may be transmitted to attitude readouts. With a semi-analytical system (one of many types of INS), the platform is always held tangential to the earth's surface. Since the platform is always horizontal and the pitch and roll synchros are set at zero when the vehicle is in a straight and level course, the pitch and roll attitude of the vehicle can always be measured directly by those two synchros.

The gimbal system can be controlled by gyro outputs. As the inertially stable part of the gyro is displaced from the case, an associated error signal is developed at the pick-off. This signal is amplified, resolved and sent to the torque motor which drives the gimbal and the case of the gyro to a position that nulls the pick-off.

The necessity for resolving the gyro pick-off (error signal) can be realized by considering the fact that the gyro coordinate system does not remain fixed to the vehicle coordinate system when the vehicle moves. For instance, a motion along the longitudinal axis of the vehicle will affect one

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or possibly all of the gyro cases depending upon the relative position of the stable element and the vehicle at a particular moment.

2.3.7 Platform Alignment and Control

The celestial sphere has been used for navigational purposes for some time. It has an equator which is formed by the extension of the earth's equatorial plane, and it has a "non-rotating" reference meridan which passes through a celestial reference called the first point of Aries. It is against this meridian that a star day is reckoned. The revolution about the earth's spin axis is calculated at 23 hours, 56 minutes, and 3.4 seconds as computed in solar time. To keep a platform tangential to the earth's surface, it and the gyros which control its orientation, must share the earth's sidereal (star) angular rate, 15.04 degrees/solar hour. This calls for "gyro correction" for the earth rate term and is an additional function of the gyro torque controls.

Regardless of where a platform is, its coordinates must be rotated at full earth rate values around some line parallel to the earth's polar axis. Just how this is accomplished by torquing individual gyros is a function of how the platform's X-Y axes are oriented relative to the earth's east-west coordinates and where the platform is in terms of latitude angle. The platform plane (as defined by X and Y) is always horizontal, relative to the earth at its position, and Z is always vertical. In most semi-analytical systems, the horizontal axes are held parallel to the latitude-longitude system.

The requirement for earth rate control stems from the fact that the earth's coordinate system is rotating. A second requirement for control concerns the fact that the earth's surface is curved. In order to keep the platform tangential to the earth's surface, control must be exerted to compensate for curvature (which varies with latitude). This type of control is called transport rate control.

2.3.8 Platform Corrections

An inertial navigation system has certain inherent errors when used for terrestial navigation. The inertial components, namely the gyros and accelerometers, are ideally suited for use as measuring devices in an environment where there is no mass attraction and no angular motion (in idealized inertial space). However, in terrestial navigation applications, both significant mass attraction (earth's gravitational field) and angular velocity (earth's rotation) exist. Consequently, an INS must be mechanized to properly alter the gyro and accelerometer outputs in order that the system conform to the environment in which it is expected to navigate. These alterations are commonly referred to as platform corrections.

Centripetal Corrections:

The accelerometer has a sensitive axis. A force applied parallel to this axis results in a displacement of the suspended mass which can be interpreted as acceleration of the case. An accelerometer also has an insensitive axis, perpendicular to the sensitive axis. Forces in the plane of this axis are unfelt. If an accelerometer is rotated about any other axis in

its insensitive plane, an axis which does not pass through the center of gravity, and it is rotated at a constant angular velocity, a centripetal force develops. But since this force vector lies in the insensitive plane, it is unfelt.

If two accelerometers are combined and mounted perpendicularly, the two insensitive planes intersect to form a single axis of insensitivity. Such a device would be insensitive to centripetal accelerations caused by constant angular velocity only if the center of rotation lies on this insensitive axis. If this were the Z-axis, the platform could be held tangential to the surface of a sphere and move over a great-circle route at a constant angular velocity without any component of centripetal acceleration along the Z-axis being sensed by either the X or Y accelerometers. Note: A platform moving east-west at the equator moves radially about the earth's spin axis, so a centripetal force does exist. But in any other case where the platform moves along a great-circle route, the radial acceleration vector lies along the insensitive Z-axis.

Coriolis Correction:

When a vehicle moves along a great-circle route in the Northern Hemisphere, it must continually correct a tendency to move off to the right of its intended track by crabbing a slight bit to the left. The reason is fairly simple: the great-circle route is rotating counterclockwise inside the celestial sphere. To follow it as it turns, a vehicle must also turn. The amount of turning at a particular point is a function of the latitude of that point. This effect, coriolis, manifests itself as an additional acceleration to the left of any path of motion in a plane which is rotated positively about a third axis perpendicular to that plane.

An inertial platform's accelerometers will measure the curvature of a vehicle pursuing a constant direction in earth coordinates. If the platform is one which has X-north and Y-east, corrections are made to the first integrator in both the X and Y channels.

2.3.9 Schuler-Tuned Platform

Any pivoted mass which is not perfectly balanced is, by definition, a pendulum. Perfect balance is a highly desirable, never achievable, manufacturing process. This holds for the manufacture of inertial platforms and all devices designed to provide a vertical reference for a moving vehicle. Such devices behave as do all pendulums. They align to dynamic vertical when at rest and tend to break into a natural period of oscillation when the vehicle is accelerated.

It can be experimentally shown that the closer the pivot axis is brought to the center of gravity, the lower the period of oscillation will be. If they are brought close enough together, the center of turning can be made to coincide with the center of the earth. Once such a pendulum is brought to static rest, accelerations of the pivot axis cannot cause the pendulum's longitudinal axis to form any angle with the gravity vector other than zero. All horizontal velocities will be accompanied by the proper angular velocities to maintain constant alignment of the pendulum to the rotating gravity vector. The pendulum will not oscillate because of horizontal accelerations.

To prevent vehicular accelerations from causing an oscillation of the stable element in INS, the platform is mechanized to have an equivalent length of pendulum extended to the earth's center. Any acceleration of the platform is about the earth's center of mass and that of the mechanized pendulum's center of mass. However, any errors that would produce an offset in the system causes the effective mass of the mechanized pendulum to be displaced and introduces an oscillation, with a period of 84.4 minutes, to the stable element (period described by German engineer, Maximillian Schuler). Errors can therefore be averaged out over that period.

2.3.10 System Alignment

The accuracy to which the navigation problem is solved depends largely upon the accuracy of the initial conditions. Therefore, system alignment is of paramount importance.

System alignment consists of creating coincidence between the platform and computer axes. There are three general methods of accomplishing this: (1) the system is slaved to an external reference source, (2) the system may have built-in capability to sense misalignments and correct itself, or (3) a combination of both of these methods.

External references take three basic forms: terrestrial, celestial, and inertial. The terrestrial system uses surveyed lines, benchmarks, plumb bobs, and bubble levels. This method is capable of providing 10-second level and 3-minute heading accuracies. Celestial information is usually obtained from star trackers and radio sextants with achievable accuracies to 10 seconds (1). When an inertial system is used as an alignment source, accuracies depend upon its initial alignment source and the time since last alignment. This system is usually used as a portable alignment tool and only intended for use when primary sources cannot be used (are not available).

The use of an external reference system requires the use of transfer devices to introduce the reference information to the system. These devices may be either optical or electro-mechanical. Optical methods are able to produce accuracies of a few seconds of arc, but the electro-mechanical are good to only about one-half minute of arc.

In self-alignment, the inertial sensing elements sense the deviation from the desired position. In order to determine the orientation of a three-axes orthogonal coordinate system, it is necessary to have at least two non-collinear reference vectors. The earth's spin vector and mass attraction vector serve this purpose.

The function of self-alignment is often divided into three modes: (1) rough alignment, (2) fine alignment or leveling, and (3) gyro compassing. For rough alignment, the gimbals are slaved to their own synchro outputs or to some external source which has a particular orientation with respect to the vehicle. Fine alignment or leveling is accomplished by rotating the platform axes to the computer axes. Once a level plane is established, the entire position of the platform is not known until the angle of a vector lying

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in a plane with a second reference vector is known. This is done by gyro compassing. With a north pointing system, for example, this is accomplished by rotating the platform axes.

2.3.11 Types of Inertial Navigation Systems

Inertial navigation systems are generally considered to be comprised of five types; analytical, semi-analytical, geometric, strapdown, and hybrid. The hybrid system could incorporate any of the other basic types. For this reason, it will be discussed in the next section.

Analytical

The analytical INS uses a platform with a fixed angular reference to some point in inertial space. No attempt is made to force the accelerometer input axes to a preferred alignment with respect to earth. This method does not require gyro torquing and as a result, the platform is subject to errors of gyro drift only.

Because the platform remains rigid in space and rotates about the earth, the output accelerations become complex. They essentially consist of two major accelerations, the actual acceleration of the vehicle and the gravitational acceleration. For navigation purposes, only the vehicle accelerations are required and therefore, the gravitational accelerations must be cancelled out. This is a difficult cancellation and requires an enormous amount of computer data.

Semi-Analytical

The semi-analytical system is the most common INS in use today. Its chief advantage is an economic one, in that the platform gimbal structure is simple and the computer functions are easily mechanized by either analog or digital means.

The semi-analytical INS maintains the stable element normal to the earth's gravitational vector at all times. The computer converts the output accelerations to angular velocities. These angular velocities are then used to torque the platform gyros to maintain normalcy with the earth's gravitational field. To prevent the platform from precessing off level due to the earth's rotation about its polar axis, the computer also develops signals equal to the angular velocity of the earth resolved into the system axes and applies them to the gyro torquers.

Geometric

The geometric INS uses a gyro system which, as with the analytical system, is referenced to inertial space in a non-rotating plane. The accelerometers, however, are mounted on a gimbal structure in a manner so as to remain perpendicular to the earth's gravitational field.

When the platform is aligned at the equator and then is moved north, the gyros maintain their position in inertial space. The accelerometers remain in a plane tangent to the earth's surface at all times.

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The main advantage of this system is that the gyros are not torqued. Therefore, scaling of the gyros is not critical. The major disadvantage is economy. Mechanizing the system requires a high degree of accuracy in the latitude and longitude gimbals; an expensive operation. The semi-analytical INS requires much less machinery precision to achieve similar accuracy.

Strapdown

The distinguishing feature of the strapdown INS compared to the conventional gimballed INS is the absence of the gimballed reference table. The system's gyro, e.g., ring laser gyro (RLG), and accelerometers are mounted directly to the vehicle's frame. The computer replaces the familiar gimbal structure.

The strapdown system imposes severe requirements on its gyros. Since the gyros measure the vehicular rotation directly, they must operate over a wide dynamic range. The rate-integral gyro is most often used for this application.

The choice of accelerometers is not critical. Those with incremental outputs are desirable as their outputs can be directly applied to a digital computer. The accuracy of the strapdown INS is limited by the accuracy of the inertial sensors and the computer used in the system.

2.3.12 Hybrid Inertial Navigation Systems

The hybrid inertial navigation system is a combination of an INS and some other type of navigation system for the purpose of updating or improving the accuracy of the INS. These systems are typified by the following:

1. Radio Inertial - A navigation system employing an INS updated by a radiodetermination system such as Loran-A or C.

2. Doppler Inertial - A navigation system employing an INS updated by velocity signals obtained from a radar, laser, or acoustic doppler system.

3. Stellar Inertial - A navigation system employing an INS and an optical star tracker to eliminate the effects of gyro drift on the inertial platform.

Radio INS have complementary characteristics that can be integrated to provide performance greater than either system used by itself. The INS is not subject to external interference, has a self-contained reference system and is characterized with errors that grow with time. On the other hand, radio navigation systems are subject to external interference, have earth-based reference systems and are not subject to the accumulation of errors with respect to time. Each system complements the others. The INS can provide naivgation through areas of poor radio navigation and the radio system can take out long-term INS errors.

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In a typical Radio INS, Loran is used to damp the Schuler loop variations of the inertial velocities and update present position. The Loran signals used are differentiated position changes of the hyperbolic time-difference measurements.

Radar doppler is normally associated with airborne INS, whereas acoustic and laser doppler systems are more closely associated with shipboard INS. Both laser and acoustic systems contain small velocity errors (less than one nmph), but these errors do not accumulate with time as do the INS errors.

Steller INS requires very accurate and up-to-date star information. And, even with excellent information, accuracies on the order of tens of feet are difficult to obtain, since a single-arc second of telescopic misalignment corresponds to 100 feet of position error.

2.3.13 Operating Procedures for a Selected Terrestrial Inertial Navigation System

An investigation has revealed that, although many manufacturers produce INS designated for aircraft or space vehicle use, only a few companies produce equipment that is designated as, or projected for use as, marine INS; Honeywell produces SPN/GEANS, Litton Systems produces the AN/WSN-2 Model 2, and Rockwell International produces MINISINS.

Honeywell's SPN/GEANS, a gimballed electrostatic gyro aircraft navigation system, was developed under contract with the U.S. Air Force. At present, the system is being used exclusively for aircraft, however, the company has demonstrated applicability to terrestial operations with a system which was test-deployed on the U.S. Navy survey ship COMPASS ISLAND.

Litton's AN/WSN-2 stabilized gyrocompass is being installed on several U.S. Navy vessels. The gyrocompass was manufactured with inertial grade components and Litton is presently attempting to market the AN/WSN-2 Model 2, as an inertial navigator. The Model 2 converts the original model to an INS by expanding its computational facility through memory and software additions plus some additional control/display functions. The expanded system is not known to be installed anywhere as of this writing.

The one known system that is presently installed as shipboard INS is the Rockwell International MINISINS, miniature ships' inertial navigation system. A dual version of the system is presently being installed aboard U.S. Navy attack class nuclear submarines. Its Navy designation is DUAL MINISINS (AN/WSN-1(V)2). As the (DUAL) MINISINS is an installed and operating shipboard system, whereas the other two systems noted above are not, its operating procedures were selected for presentation here:

Normal turn-on of the MINISINS is accomplished by confirming that primary power is available, selecting the navigation mode (switch selectable) and placing the primary power switch in the "ON" position. Subsequent automatic operations will sequence the MINISINS through preparatory steps. Two sequences are possible in the DUAL configuration. The channel being started may quickly "SLAVE" align to the operating channel or may "self-align" in two to four hours using inputs from the ship's EM log and/or other available position resets.

The operator has the choice of allowing automatic or manual start-up. In automatic, system status can be monitored by typeouts or indicator lights. In manual, the operator must first select "CAGE" mode. This provides coarse platform alignment to the ship about the pitch and roll axes and an operator-inserted heading angle or the heading angle of the other MINISINS channel. The operator must next select "SELF-ALIGN" or "SLAVE ALIGN" mode. The self-align mode provides fine inertial measurement unit (IMU) platform alignment to local vertical and geographic north and compensates gyro drift rates. The EM Log velocity is used as reference for all at-sea alignments. The slave-align mode enhances fine alignment and gyro drift rate estimates by using velocity and heading information from the other MINISINS channel. After the system has been in the align mode for two or more hours (depending upon desired accuracy), the system may be advanced to the "NAVIGATE" mode for normal operation of the system. The only remaining operator function would be to enter an external position fix as desired, so that a reset filter can estimate and apply necessary corrections to position errors and gyro drift rates.

Optional operator functions are available on command. Schuler damping and use of the EM Log input can be engaged/disengaged as desired.

2.3.14 Accuracy Considerations

Error sources in a marine inertial navigation system can be classified as:

1. Improper initial conditions errors

2. Accelerometer and gyro drift rate errors

3. Data handling errors

4. Reference velocity errors

Improper initial conditions include earth rate, latitude, and heading angle inputs as to the mechanical alignment of the inertial measuring unit (IMU) to the platform (ship). The latter condition is a function of the original or possible subsequent IMU installation/replacement. This alignment is best done using optical means. Accuracies to a few arc seconds are possible. The other initial conditions which affect accuracy are within the user/operator's purview.

Accelerometer and gyro drift rate errors are gyrocompass functions. These were discussed in Subsection 2.1.8.

Simply, data handling involves inputting raw data to a computer which operates on the data to provide desired navigational information. Two important error-producing functions are resident in data handling, computer truncation, and estimating with mathematical models. Computer truncation is addressed in Subsection 2.1.8. There are several mathematical models which may be used in INS computer software. Some of these are used to represent such factors as the variations of the non-homogenous gravity vector, earth rate terms as a function of longitude and latitude, weighting factors for inputs

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that affect determination of navigation parameters and so forth. Errors result as the estimated values depart from the actual values.

A considerable amount of work has been done to decrease the dependence of INS on external reference aids to damp velocity errors and/or update present position information. This has resulted in INS capable of providing relatively accurate position information for longer periods of time, but has not obviated the need for such reference aids, especially for those applications in which extreme accuracy is required. One commercial system (2,3) can provide an unaided position accuracy of less than 200 meters per hour and a velocity damped accuracy of 10 to 30 meters per hour (of travel) relative to initialization. The accuracy of an INS that is updated with "true" position information depends on the accuracy of the "true" position and the amount of error growth of the unaided or damped system since the previous update.

The rationale for damping with a reference system is quite simple. It is well known that the altitude channel of an unaided INS is unstable and that the horizontal channels, while not unstable, are undamped and, therefore, only marginally stable. Altitude instability is commonly corrected by employing an external altitude measurement (e.g., barometer). For marine applications, computer corrections can be made using a model of the "reference geoid" (model's gravity variations). The unbounded growth of navigation errors (horizontal) of an unaided system can be "damped" by use of an external velocity measurement such as that provided by differentiated position changes of a hyperbolic navigation system such as Loran-C. When used for damping, error effects due to geometric dilution, clock accuracies and propagation uncertainties of the reference system must be included in the INS error budget.

2.3.15 Potential Application to Buoy Tending Operations

Historically, inertial navigation systems have been primarily used for aircraft navigation and missile guidance. The high rate of speed of these vehicles coupled with small error growth rates of INS produce small position offsets between actual and desired destinations. For example, a 200 meters per hour offset (as noted in the previous section) would convert to a total error of about 1.0 kilometer for the typical commercial coast-to-coast air flight. If the same system were damped with an external reference aid, the offset could be in the 50 to 150 meters range. Either way, the offset is well within FAA flight lane tolerances and sufficient to locate and switch to ground control for final approach and landing operations.

The degree of INS accuracy is, of course, relative to its application. A 50-meter offset after five hours of air flight is practically inconsequential if the aircraft is in an uncongested flight area. However, a 50-meter offset at the approach to a runway could be disastrous. And likewise, a 50-meter offset after only five hours of underway time would surely limit the ability of a Coast Guard buoy tender to accurately position a buoy.

Let us consider some possible applications of INS to buoy tending operations. For this exercise, buoys will be considered to be near shore in areas where fixed horizontal control is available in sufficient quantity, near shore in areas where fixed horizontal control is not sufficient or offshore

where no fixed horizontal control is available and electromagnetic systems may
or may not be available. For near-shore applications, it can be simply stated
that if horizontal control is available, their use would most likely produce
greater accuracy than INS. If horizontal control were not available, the INS
which needs (for optimum accuracy) reference data for calibrating damping and
updating would be adversely affected. For offshore applications, it could be
proposed that the position accuracy required for an aid to navigation is not as
great as that of near-shore aids. This, then, is an area in which an INS might
be useful. However, in order to determine usefulness, several factors must be
taken under consideration: Loran-C will, in the near future, provide coverage
of the entire U.S. coastal confluence zone. With proper calibration and high-
resolution receivers, the accuracy of this system may be sufficient for some
offshore buoy positioning. Radar and satellite methods might also be useful.
There are also a number of portable short-to-medium range radio-wave systems
that are claimed to provide good accuracy. The usefulness and implementation
cost of all these systems are projected to be better than that of the INS.

        In summary, INS is a sophisticated dead reckoning system which
is adequate for general navigation, but not for high-accuracy survey applications.

2.3.16 Safety Considerations

        There are no special safety requirements for inertial naviga-
tion systems. Certain hazards might exist in electronic or electric circuits
and the rotating portions of the inertial measuring unit such that maintenance
personnel must exercise well-known precautions, but operating personnel are not
generally exposed to any of these possible hazards. It is noteworthy that all
of the marine INS discussed in Subsection 2.3.13 have been designed to military
standards.

2.3.17 Characteristics of an Example Marine Inertial Navigation System

        An informal survey by the Coast Guard R&D Center has revealed
that only one INS, Rockwell International's MINISINS, is currently operating as
an installed marine INS. The dual version, dual MINISINS, AN/WSN-1(V), is
being installed on all new attack class U.S. Navy nuclear submarines (as noted
earlier). The characteristics of this system as presented by Rockwell Inter-
national (4) are summarized in Table 2-3.

2.3.18 Conclusions

        An unaided inertial guidance system has a characteristic that
navigators of the past could only dream about and that present-day navigators
can enjoy, a self-contained navigation system. The navigator need only enter
a starting location into the system and start his mission. Subsequent position
information provided by the system will be characterized by a small but ever-
increasing error which is common to any undamped system. Depending upon the
length (time) of the mission, the error growth rate and the navigator's allow-
able error, he might be able to complete his entire mission without updating
his system with a "new" starting location.

Unaided inertial navigation systems have been demonstrated to provide position inaccuracies of better than 200 meters per hour, which in some navigation applications is quite suitable. But, in order to achieve a greater degree of accuracy, the INS must be damped with an external reference velocity measurement and/or updated with "true position information." There are methods of damping, e.g., EM Log, that would maintain the identity of the INS as a self-contained navigation system, although most methods of damping and position updating require a source external to the operating vessel, thereby removing the "self-contained" flag. Depending upon many factors, including the damping method and position update intervals, an INS can be "forced" to provide position inaccuracies approaching 10 meters per hour for long-term navigation.

The standard INS accuracy criterion, offset per hour, is especially descriptive for navigators. They generally have a good estimate of the travel time for a particular mission and can easily estimate the approximate position accuracy that the INS can offer for that mission. In this regard, a typical one-day Coast Guard buoy-tender deployment would result in an at-best position accuracy of somewhere near 100 meters towards the end of the day. This type of accuracy, although quite good for general navigation, is not sufficient to achieve any survey-level results, which includes positioning buoys.

Inertial systems have come a long way in increased accuracy during the past decade and industry is predicting that inaccuracies will be halved in the next decade, but even if that goal is reached, INS will not be capable of providing high order survey work like that required for Coast Guard buoy positioning.

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TABLE 2-3

CHARACTERISTICS OF DUAL MINISINS

CHARACTERISTIC

MTBF:	1256-2106 hours per channel 5040-8400 hours for dual system
MTTR:	16.3 minutes
Repair philosophy:	Unit or module replacement
Spares:	Small amount;due to repair philosophy
Weight:	3000 kilograms
Volume:	2.0 cubic meters
Power:	115 VAC, 400 Hz, 3 phase (delta), 6.2 KW
Cooling:	Forced compartment air
Start-up time:	2-4 hours
Calibration interval:	Self-calibrating, operator-controlled
Training requirements:	Minimal for operators, more extensive for maintenance personnel, U.S. Navy schooling available
Cost:	Approximately $1 million for completely installed dual system[a]

[a] Cost for a single-channel system not available; for comparison purposes, acquisition costs of other single-channel inertial navigators is estimated to be $140K to $200K.

2.4 Radiodetermination Methods

2.4.1 Introduction

Navigation by radiodetermination methods is as widespread as the radio frequency band, starting with Omega at 10-14 kHz and continuing to satellite applications at 250-265 GHz. Along the spectrum are radar and tracking systems at several discrete frequency allocations between 70 kHz and 36 MHz; Loran-C, Loran-D, and Decca at or near 100 kHz; maritime radio navigation and direction-finding systems near 300 to 400 kHz; a host of marine navigation and positioning systems such as Loran-A, ARGO, Lorac, Decca Hi-Fix and Sea-Fix, and Raydist in the range from 1.6 to 5.0 MHz; aeronautical beacons, ranges, landing systems and radar systems at several frequencies between 200 kHz and 16 GHz; several commercial hydrographic survey systems such as Autotape, Maxiran, Miniranger, and Tellurometer in the range of 250 MHz to 10 GHz; and other satellite and space vehicle applications from 43 to 250 GHz.

The scope of this report limits examination of the above listed radio systems to a manageable portion of them. Omega, Loran, and radar are not examined here as these systems are being treated in another report being developed concurrently with this one. Maritime radio navigation and direction-finding systems at 300-400 kHz are not designed for precision navigation, so those systems are not discussed. Aeronautical navigation systems are not relevant and satellite systems are discussed in Section 2.5 of this report. That which remains is commercial hydrographic survey and marine navigation systems. In this section, these systems will be analyzed for application to buoy-tending operations by coverage, short and medium range; by configuration, circular or hyperbolic ranging and range/bearing; by user operation, active or passive; and by technology, CW, pulsed and microwave modulated transmissions.

2.4.2 History

The roots of navigation by radio methods can be traced back to the latter part of the nineteenth century and James Maxwell who theorized that alternating voltage and current would radiate electric energy in a manner similar to wave motion. He called this electromagnetic radiation and determined its velocity of propagation as being about 3×10^8 m/sec. A German physicist, Heinrich Hertz, proved Maxwell's theory in 1887 and also noted that radio waves were reflected from solid objects and could be formed into beams with metallic conductors or antennas. In 1902-1905, Guglielmo Marconi, an Italian inventor, developed the first horizontal directional antenna, an important step towards the development of radio aids. Marconi also determined that, since radio waves travelled further at night, some sort of atmospheric layers must be present to cause reflection of the radio wave energy. Arthur Kennelly and Oliver Heaviside concurred with Marconi by their postulation of the ionosphere in 1902. The existence of the Kennelly-Heaviside layer was verified and its height measured in 1925 by Gregory Breit and Merle Tuve of the Carnegie Institute. The measurement was accomplished by transmitting a short series of electromagnetic pulses and measuring the elapsed time until the pulses were reflected back to earth by the ionosphere. The distance was determined by multiplying 3×10^8 m/sec by one-half the elapsed time. Distance measurement in the reverse direction, air to ground, was accomplished in 1928 by W. L. Everitt using a radioaltimeter which he had invented.

World War II provided the impetus for the development of many radio ranging systems, such as radar, Gee (forerunner of Loran-A), Decca, and Shoran. The latter was converted from a wartime air navigation systems to a long-range surface and air aid. In the late 1950's, Tellurometer introduced the first instrument to use microwave modulation for precise geodetic surveying. Since then the radio navigation and surveying industry has virtually exploded into a very large business. Applications vary from short-range aircraft instrument landing systems to worldwide navigation systems such as Omega; from precise terrestial surveying to space applications; from simple handheld user equipment to complicated computer-controlled user systems; from kilohertz to gigahertz operating frequencies; from peaceful commercial ventures to highly strategic military operations and so one. And, the end is not in sight yet, as manufacturers compete to develop more accurate, more utilitarian, and less expensive equipments.

2.4.3 RF Propagation

The velocity of propagation for RF radiation is constant in a vacuum at approximately 300,000 km/sec. However, the velocity is reduced within the earth's atmosphere due to density variations within the several atmospheric layers. A measure of the reduction is indicated by a parameter called the refractive index. In a vacuum, the index is unity whereas in a so-called standard atmosphere, it is about 1.0003. Fluctuations about the latter value are caused by variations in temperature, pressure, humidity, and wavelength. Humidity is the most influential of the factors; wavelength is the least (31).

The effect of refraction is to cause bending of radio wave ray paths as the rays transit layers of varying refractivity. They tend to bend toward the direction that supports a lower velocity of propagation. Since, in general, refractivity decreases (approaches unity) with an increase in altitude, radio waves bend downward with the earth's atmosphere. This results in a so-called radio horizon which extends slightly beyond the optical horizon (depending in part on the amount of bending), thus extending the line-of-sight (LOS) and advancing the concept that the shortest radio-distance between two points is a curved line.

Throughout most of the radio spectrum, the radius of curvature of ray paths is greater than the earth's so that beyond LOS the main body of a radio signal departs from the earth's surface, escapes the atmosphere and encounters the ionosphere. Depending upon several factors which include ionspheric electron density, wavelength, and incident angle of the wave with the atmosphere/ionsphere boundary, the wave (sky wave) may be all or partially reflected toward a remote earth location or continue into space. It might also be trapped between two ionspheric layers and reflect back and forth (ionspheric ducting) until exiting towards the earth or space.

There are some areas within the radio spectrum that the foregoing general discussion does not hold exactly true. In particular, the propagation factors are somewhat different in the VLF/LF and microwave regions. At VLF/LF frequencies, ground conductivity becomes a predominant factor over any atmospheric effects. As the wavelength is increased, the conductivity increases

so that signals follow the earth's curvature (ground wave) and may propagate at distances far in excess of the horizon.

At microwave frequencies, two more important propagation phenomena become apparent; ground reflections and tropospheric ducting. Ground reflections are similar in nature to ionspheric reflections in that an incident wave strikes a boundary of abruptly differing propagation characteristics and "skips." As is also true with ionospheric reflections, the wave may reinforce or interfere with the signal arriving at a remote point via the most direct route, e.g., ground wave. Tropospheric ducting can occur within a somewhat undefined band of frequencies ranging from upper VHF through lower UHF. Within this band, signals can propagate in the duct formed by the tropopause (troposphere/stratosphere boundary) and the earth's surface. This allows for signal reception significantly beyond the optical horizon.

The relevance of ray paths and propagation velocity is apparent when one considers that most all radio navigation and survey systems rely on the measurement of the time it takes for a signal to travel a most direct route from/to transmitting and receiving sites. Anything other than the most direct routing will introduce delays in the arrival time of the signal. This is commonly referred to as multipath propagation and can produce time-of-transit measurement errors, cause distortion of most directly routed signals or cancel them unless countermeasures are employed. Since it is most impractical to determine empirically the average propagation velocity (especially over long routes of varying earth's surface conditions), it is common practice to apply a standard value to the time/distance formula. Any difference between the actual and standard values will introduce errors in the determination of ranges from time-of-transit measurements.

2.4.4 RF Transmission Techniques

Three methods of signal transmission are common to radio navigation and survey systems, pulsed, continuous-wave (CW) and microwave modulation. Microwave modulated transmissions are actually of the CW group, however, there is a distinction in operation so they are treated separately here. Although not a rule, most lower frequency systems use CW transmissions whereas higher frequency systems use pulsed or microwave modulation transmission formats.

Pulsed-type transmission systems generally employ an active station, e.g., a responder, to return signals to the actuating station. The actuating station, called a mobile unit, originates a group of fast rise-time pulses and at the same instant initializes a precision time-interval counter. A remotely located unit, generally referred to as a base or secondary unit, replies with another group of pulses after arrival of the mobile signals. The time-interval counter stops when the remote signal is received at the mobile unit. Range is then calculated by multiplying the elapsed time by the velocity of propagation and dividing by two. Additionally, any delays inherent or incorporated in the mobile and base equipments must be subtracted from the observed elapsed time. Inter-transmissions may be on different frequencies and the pulses may be so coded as to make the individual mobile and base unit transmissions distinguishable. Multiple-user operations are generally limited

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to less than ten simultaneously, with only a single user possible with some systems.

There are several CW methods which are employed in radio-ranging, but all methods have one idea in common: all measurements at a point are made by phase comparison of two signals. The phase relationship indicates the difference in path lengths traversed by the two signals. These two signals can either be a reference and an unknown or both unknown. One CW method uses pairs of base units which transmit phase-locked harmonically related signals. At the mobile unit the arriving signals are multiplied by harmonic numbers to produce pairs of comparison frequencies which represent phase differences. The comparison is done and a local lattice chart developed with respect to the comparison waves. Another method operates with phase-locked signals being transmitted from several stations on the same frequency in a time-sharing mode. Yet another method operates without the need for phase-locking. Base stations transmit related but dissimilar frequency signals which are heterodyned down to the same beat frequency at the mobile unit and a reference station. The beat signal from the reference station is then transmitted via a radio link to the mobile unit where the phase difference between the locally and remotely generated beat note provides an indication of the movement/location of the mobile unit.

Some systems may use a combination of pulsed and CW trans-missions. Loran-C is an example in which the pulsed envelope is a coarse measure and the phase relationship of the CW carrier is a fine measure of range.

Phase measurement systems are inherently ambiguous because the pattern of phase differences repeat every one-half wavelength. For example, a 10 kHz signal repeats its phase every 15 kilometers, and a 10 MHz signal repeats every 15 meters. In order to achieve a large unambiguous range and yet maintain a fine resolution, both example frequencies are modulated onto a CW carrier. In this case, the system resolution would need to be some value slightly better than 1:1000 so that the coarse measurement capability is better than 15 meters. This resolution would theoretically lead to an overall 15-mm resolution for the example system. A technical advantage of this method is that the required resolution of the phase measurement circuitry is reduced by an order of 100. In actual practice, phase comparisons of several modulation frequencies are used to provide a large unambiguous range, and coarse, medium, and fine range resolution. This transmission method, called microwave modulation, is potentially more accurate than pulsed or other CW methods.

2.4.5 RF Navigation and Positioning Techniques

Three techniques are most common to RF navigation and position-ing: circular, hyperbolic, and range/bearing. The latter method is least often used and the other two methods are used about equally. Range/bearing techniques, often referred to as rho/theta, have limited application because of the expense (manpower and/or equipment) involved in bearing trackers and also because of accuracy limitations imposed by minimum achieveable angular resolution of such a system. In this type system, a range is obtained by any of the conventional methods noted in the previous section. Bearings may be obtained from an automatic or manual, optical or microwave tracker. Radar is an example of a rho/theta system.

When position is determined by the intersection of two or more ranges from two or more known locations, the method is called distance intersection, or most commonly, the circular approach. In fact, intersection occurs at two points (intersecting range circles) but the ambiguity is generally easily resolved since navigators usually have a good knowledge of their approximate locations. In the case of base units located at points along the shoreline, one intersection set will generally occur inland. The circular technique is very popular with portable systems. Positioning is accomplished with respect to a locally generated reference grid.

Hyperbolic techniques include operation in a portable manner with reference to a local grid, and fixed-type systems which use prepared nautical charts. Hyperbolic LOP's are generated from pairs of time difference readings, e.g., the difference in the time of arrival (TOA) of two remote signals. Loran-C is an example. Ambiguity comments for circular techniques also apply to hyperbolic technique.

There are no intrinsic differences in the circular and hyperbolic approaches, since both fundamentally rely on signal TOA to determine position information. There are differences in operations and results though, and these are best dramatized by considering a passive user system (mobile unit receives only) employing a circular technique and a passive user system employing a hyperbolic technique. The circular equipment for this comparison indicates position with respect to a local grid and the hyperbolic equipment with respect to a prepared chart. Precise knowledge of system time is not necessary for the hyperbolic system as the user needs only to measure the time difference between two pairs of arriving signals for plotting on a chart. On the other hand, a circular system user requires a precise knowledge of system time as ranges to the remote units are a function of the time of arrive minus the time of transmission. This necessity can be eliminated for active user circular systems (mobile unit transmits an interrogation signal and base unit responds). In the case of an active user, the time of transmission at the mobile unit is known. However, a possible disadvantage of the active user circular system is that users are limited by multiple response capabilities of the base stations.

Continuing with the passive circular system, another of its characteristics is the requirement for position initialization. The mobile unit must be located at a point where the exact distances to the base units are known or can be calculated. Movement away from this point is then calculated by tallying whole and partial lane crossings. A lane is defined as the distance equal to one-half wave length of the lowest modulating frequency. If for some reason (i.e., equipment malfunction) the lane tally is lost, the system must be re-initialized. This would require the user to return to the original initialization point unless another more handy location or position reference is available. On the other hand, hyperbolic systems require no initialization and are not subject to loss of position reference.

An advantage of the circular approach over the hyperbolic approach is that it requires one less base station for systems of comparable number of independent LOP's. Other advantages are that a lattice constructed of circular LOP's maintain a constant gradient throughout the service area and provide a direction sense which is directly relatable to the location of the

base stations. That is not the case with a hyperbolic grid. There are at least two benefits here: the effects of system errors are more uniform throughout the service area and surveyors can more easily visualize vessel movement with respect to grid coordinates, an important practical aspect. Much more can be said about the advantages/disadvantages of the hyperbolic versus circular approach, especially as applies to dissimilar error effects, but that is beyond the scope of this report and is an objective of other research being conducted at the Coast Guard R&D Center, National Ocean Survey, and the U.S. National Bureau of Standards.

2.4.6 Operating Principles of Electronic Control Positioning Systems

Four commercially available systems, Autotape, Maxiran, Raydist, and Trisponder, have been selected for examination here. The selection was based on availability of information and because they collectively encompass most of the various technologies involved in electronic control for hydrographic surveys Each system has several competitors which employ basically similar operating methods. Some of the most widely used of these systems are compared to the following systems in Tables 2-4 and 2-5:

Autotape

The Autotape (DM-43) system is manufactured by Cubic Corporation. It is a phase measurement system which employs microwave modulation of a 2.9 to 3.1 GHz carrier frequency. It is operated with an active mobile unit which interrogates 1-3 base units. Position determination is by circular ranging, which can be accomplished by only a single user. The maximum operating range is 150 km (LOS). The mobile unit and all base stations transmit a discrete frequency CW signal for identification purposes. All transmissions are phase-modulated with a common set of three frequencies. The base station equipment demodulates the mobile signal and uses a phase comparator circuit to phase lock the three modulating frequencies. The mobile equipment simultaneously receives, demodulates, and does phase comparisons for all base station signals versus the mobile signals. The choice of modulating frequencies provides an unambiguous range of 10 km and a system resolution of 10 cm.

Maxiran

Maxiran, a product of Navigation Management, Inc., is also known as S.S.A. Hiran (Solid State Automatic). It is a pulse measurement system which operates within the band of 420 to 450 MHz. Beyond LOS propagation ranging to 240 km results from tropospheric (surface) ducting. The active mobile unit can interrogate any three of up to six base stations simultaneously. Position determination results from circular ranging techniques. Up to eight system users can be simultaneously accommodated. The mobile unit measures the round trip time interval of specially coded pulses. The process is started when the mobile unit initiates a pulse which is used for time initialization and to trigger a phase-code generator. The phase code generator develops a 14-microsecond 127-bit pulse which is phase shift modulated onto an RF carrier. Two of these pulses are transmitted at selectable spacings of from 26 to 60 microseconds in order to allow selective interrogation of the base units. The base unit, upon recognizing its code, processes the 127-bit pulse through an

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acoustical wave device which delivers a single pulse that is approximately 100 times greater than the level of the individual bits. The pulse is used to trigger a responding 127-bit pulse. This response is similarly handed in the mobile unit where the initial and responding pulses are compared to measure elapsed time and determine range.

Raydist-T

The Raydist-T is one of a family of systems which are manufactured by Teledyne Hastings-Raydist. It is a phase measurement system operating on a CW and an SSB frequency in the range of 1.5 to 4.0 MHz. Its maximum operating range is 400 km, relying on ground-wave propagation. Four base stations and a passive mobile unit are required for this system to operate with two LOP's in the hyperbolic mode. Other equipment configurations are possible, i.e., the Raydist DRS-H requires three base stations and an active mobile unit for circular mode operation. When in operation, two Raydist-T CW transmitters at separate locations each broadcast continuously. The frequencies of the two signals differ by several hundred hertz. One of these transmissions is received at one of two additional base sites where it is heterodyned with a third frequency. The difference signal is then transmitted SSB. At the mobile unit this heterodyned tone is also generated in the same manner. The two tones are then phase-compared to obtain a time-difference measurement (hyperbolic LOP). The same operation occurs with the other sets of stations, only a fourth frequency is involved and transmissions from the fourth station are on the opposite side band from that of the third station. Intersection of the two hyperbolic LOP's is an indication of position.

Trisponder

The Trisponder system is marketed in the U.S. by Del Norte Technology, Inc. The Trisponder 202 is a pulse measurement system operating with different mobile and base station frequencies in the range of 9.3 to 9.5 GHz. Operating range is 80 km (LOS). Measurements of time of transit are made by an active mobile unit on signals transmitted by two of the four possible base stations. The mobile unit sequentially transmits two trains of coded pulses each second. The pulses are 0.5-us duration and the coding identifies the base station being interrogated. The base stations decode the pulses and reply with their own coded pulse train. The mobile equipment develops a range measurement by averaging the elapsed round trip time of 100 pulses.

2.4.7 Operating Procedures

Based on available literature and R&D Center testing, the following steps must be taken to prepare for proper operation of a radiodetermination system.

(1) Select the most likely sites for placement of base station equipment.

(2) Visit sites and determine availability and accessibility.

(3) Verify good LOS to operating area for LOS systems.

(4) Attempt to avoid areas which contain large reflecting surfaces such as large buildings or cliff faces. This is most important for microwave operating frequencies.

(5) Ensure the operating area is within the useful range of all base stations.

(6) Ensure the beamwidth of the base station antennas are sufficient for the coverage area and deployment geometry.

(7) Evaluate the system geometry to determine that the crossing angles of all LOP's and the grid gradients are acceptable.

(8) Plan antenna height so as to reduce ground reflection effects while minimizing other multipath effects and allowing for necessary LOS range.

(9) Determine geographical position of the electrical center of the base station. This must be done to the highest possible level of survey accuracy, and must be expressed in the same coordinate system as that which is to be used for subsequent survey operations. Thoroughly document.

(10) Install base station equipment.

(11) Install mobile equipment.

(12) Calibrate mobile unit for all LOP's at the range of operation. This can normally be done by electrically forcing readouts to agree with predicted values.

(13) Proceed with mission.

(14) Record all pertinent data for purposes of post-mission analysis.

(15) Recalibrate.

(16) Deactivate system.

(17) Perform post-mission analysis in order to verify and possibly improve on any in-field survey work.

(18) Thoroughly document all work.

In-field equipment operation and data collection procedures vary between systems being utilized, but are generally quite similar. After initialization, all systems provide operators with one to three circular or

hyperbolic ranges, generally in the form of lighted digital displays. It becomes the function of the surveyor or navigator to match range readouts to predetermined values in order to sequence an event or else record the readouts as an event occurs.

Navigation and electronic surveying is considerably enhanced by means of anciliary equipment to reduce the interaction between the operator and equipment. Perhaps the most effective means is the use of a mini-computer to convert a set of range readings to a set of geographic coordinates. Another valuable addition is an X-Y plotter which can provide an actual plot of a mobile position with respect to a local grid. In addition to the X-Y plotter, data can be stored on various other mediums such as magnetic or paper tape. By using all of these equipments, the basic radiodetermination system can be transformed into a hands-off position plotting.

2.4.8 Accuracy Considerations

The principal error sources of radio-ranging systems are instrumental, multipath, propagation, and site survey related:

Instrumental Errors

Because many of these systems depend upon the measurement of transit times of signals to and from the mobile unit, variations in equipment delays induce transit time measurement errors. Constant errors are easily determined and compensated for through calibration, however, little can be done to eliminate variable errors caused by such things as temperature-dependent components and fluctuations in signal strength. Variations in signal strength leads to an inherent variation of calibration with range and requires that equipment be calibrated in each area of operation. This type of calibration adjustment is provided for in most radiodetermination equipment. Other instrumental errors concern timing and time measurement capabilities of the equipment. For those systems that require a precise knowledge of system time, highly accurate clocks and more complicated software packages are required. Both phase and pulse time measurement circuits are error prone, with pulse measurement circuits being theoretically the least accurate since they are strongly affected by pulse amplitude and distortion.

Multipath Errors

Multipath is considered a potentially large error source. It can cause direct measurement error and degradation in signal level, and is somewhat fostered by systems that employ inexpensive omnidirectional antennas at the mobile unit and low mounted antennas at the base stations. Under certain circumstances this causes reflections of the signals from the earth's surface as well as from natural and manmade prominence such as buildings, ships, and cliff faces. There are many methods employed to reduce multipath effects and most of them involve antenna characteristics and placement. Multipath rejection is accomplished to some extent by use of narrow beamwidth antennas. Further discrimination is accomplished by adjusting the height of either or both the mobile and base unit antennas. Pulse systems can potentially discriminate against these effects through rejection of all but the first return pulse.

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Propagation Errors

For microwave LOS operating systems, propagation anomolies are practically non-existent. Only a very slight bending (less than 2 cm in 65 km) (10) is caused by refraction effects of the atmosphere when operating at or near sea level. However, at the lower frequencies, 2-Mhz region, for example, ground conductivity becomes an influential factor in signal propagation. Transmission over water and land, or even over different types of each, occurs at different phase velocities. This is not a major problem when the entire path is over one type of medium, such as salt water, since appropriate corrections are easily applied, but it becomes a large problem when the path is not homogenous. Extensive land and water interfaces along a signal path cause an average phase velocity that has to be approximated by mathematical models. Emperical determination is an expensive and tedious task that is seldom satisfactorily accomplished.

Analysis of propagation anomolies for the special case of tropospheric ducting (reference the Maxiran system) is rather complicated. Propagation to about 200 km is generally predictable, but propagation out to three or four hundred kilometers and more will depend on local atmospheric conditions. At the long ranges, variations in propagation velocity does become significant and can easily produce errors of several meters. Actual ray paths vary according to the vertical lapse rate of the troposphere which is most affected by temperature variations. All medium range systems such as Maxiran can be affected by skywave contamination of the more predictable ground wave at extreme ranges. This is a particular problem with night-time operation. Additionally, almost all systems experience high noise and signal dropouts during electrical storms.

Site Survey Errors

This is probably the most fundamental error source in the deployment of radiodetermination systems. It is imperative that a good quality survey be performed to establish the electrical center of the base station location. Errors in location will contribute to overall system inaccuracy in much the same way as GDOP errors (discussed below). Also, in order to ensure the best results, site surveys should be in the same geodetic reference as that which might be used for radiodetermination by use of the system.

An effect which can produce the widest variety of positional discrepancies, as it is basically a "multiplier" of all system errors, is geometric dilution of precision (GDOP). Good geometric positioning of the base units and deployment of the mobile unit can limit this effect, whereas poor geometry can provide positional errors which are many times the ranging errors. Many marine surveyors use rule-of-thumb limits of 30° to 150° LOP crossing angles. This limits the diagonal of the error polygon as well as the major axis of the random error ellipse to approximately four times the individual ranging errors.

R&D Center analysis of two-LOP systems indicates that, given good engineering done by a specialized crew, adequate position information can be provided. Three-LOP position accuracies (95 percent confidence) of 10

meters or less for phase measurement systems and approximately 25 meters or less for pulsed systems should be achieveable.

2.4.9 Potential Application To Buoy Tending Operations

Installation of the mobile unit on a buoy tender is a straight-forward simple operation. The space requirements, installation complexity and costs would be similar to a direction-finder installation. The control unit antenna requires a near-360° unobstructed view or else certain operational limitations would be imposed, such as the requirement for the conning officer to approach a position from a prescribed direction. The most probable location for the antenna would be high atop a mast.

Since range measurements are made with respect to the location of the mobile unit antenna, another measurement consideration must be taken into account; the point at which the buoy anchor/sinker will be dropped. Although this problem is not unique to electronic control, some resolution of the difference in antenna and drop point locations must be included in position calculations.

In all probability some modification to the display capabilities of the average radiodetermination system will be required. Simultaneous range readouts are not particularly conducive to navigation and/or instantaneous position determination. An X-Y plot of position as determined by a calculator operating on several ranges is a possible solution. More elaborate methods such as mini-computer-controlled CRT indications of vessel movement might possibly be useful. Audio or visual alarm indications of arrival at a decision point is another idea.

All of the systems that are discussed in this section are more or less portable, although permanent installations are possible. Permanent installations can be so designed and/or manned to provide a measure of equipment security, a necessary consideration, but it is the nature of short-range systems in particular to be most economical when used in a portable fashion. This is emphasized by the following deployment example:

> A tender using a three-LOP system is operated in the New York Harbor Lower Bay. This area has a high concentration of Coast Guard-maintained floating aids to navigation, in all about 200. It is estimated as the result of theoretical experimentation at the R&D Center that 12 system deployments occupying 19 separate sites would be required to reasonably satisfy restrictions imposed by the range of an LOS system, available shore sites and GDOP considerations. Fewer sites would be required for a medium-range system. However, overall accuracy would be reduced.

It can be argued that the New York Lower Bay may not be the logical location for use of electronic control by a radiodetermination system. This is most likely true, but the large number of site locations and deployment configurations in an area of high floating aids to navigation density and good site opportunity points to an even larger effort in using this type of system in those areas which are not as hospitable.

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Although portability reduces the required number of base station equipment sets to be purchased for the above example, the need to deploy and redeploy the system is a major drawback. Some thoughts regarding this are: numerous site surveys are required; personnel are required to install and "baby-sit" the equipment; most portable equipments are battery powered, leading to a host of logistics problems; logical site locations are not always easily accessible; radio communications would be necessary; and the physical (and probably electrical) lifetime of equipments will most assuredly be reduced by excessive handling.

2.4.10 Safety Considerations

Radiodetermination systems do not generally require special safety precautions although normal precautions must be observed for the handling of electronic equipment. Most systems are very low in transmitted power, although some higher powered equipments will require precautions normal to those for any RF radiating system. The fact that shore-based personnel could be dispatched to areas of poor access in a variety of weather conditions leads to a host of normal environmental precautions. Base stations are normally battery operated so installation personnel could be exposed to chemical hazards, but again, only well-known safety precautions need be observed.

2.4.11 Characteristics of Example Systems

In Subsection 2.4.6, several systems' characteristics were discussed. Tables 2-4 and 2-5 include these characteristics and others for those and several competitor systems. Table 2-4 characterizes short-range systems and Table 2-5 characterizes medium-range systems.

2.4.12 Conclusions

Of all the systems examined in this report, radiodetermination systems presently have the most practical application to buoy-tending operations. It is not potentially the most accurate system, but with proper engineering, short-range (LOS) systems are capable of providing sufficient accuracy for buoy placement. It is inherent in these systems that errors increase with range such that medium-range systems, which can provide excellent general navigation information over a large area, are not suitable for use for buoy placement.

Theoretical examination of system operating techniques and modes can become quite complex, especially when different equipment production techniques are taken into consideration, e.g., different manufacturers. However, the following general rules apply: phase measurement systems provide greater potential accuracy; the choice of hyperbolic versus circular ranging is not clear-cut, however, the constant-gradient grid of a circular ranging system is potentially more accurate in the small operating area where good LOP crossing angles prevail; and circular systems employing microwave modulation offer the best resolution over a larger non-ambiguous range.

Use of portable LOS radiodetermination systems has a number of drawbacks which need to be considered. Some of the most prominent are: several deployment configurations are required to cover anything more than a

small area, leading to requirements for multiple-site surveys and additional
equipment; a contingent of shore personnel is required to deploy base stations;
and system deployment will be limited to those times and hours when weather and
light conditions allow for base station deployment. These are not disqualifying,
but are very important economic and practical considerations.

TABLE 2-4

SHORT-RANGE RADIODETERMINATION SYSTEMS CHARACTERISTICS
(1 of 3)

SYSTEM & MANUFACTURER	OPERATING MODES	NUMBER OF USERS	OPERATING RANGE	OPERATING FREQUENCY	SUPPLY VOLTAGE		MAXIMUM RF POWER
					MOBILE	BASE	
AUTOTAPE (DM-43) Cubic Western Data Corporation	Circular Phase Comp.	One	100 m to 150 km LOS	2.9-3.1 GHz	12 or 24 VDC	12 or 24 VDC	1 W
MINIRAN Navigation Management, Incorporated	Circular Phase Comp.	Six	2-45 km LOS (nom.)	2.9-3.1 GHz	115 VAC, 50-400 Hz or 12 VDC	12 VDC	450 W (4 W ave.)
MINIRANGER III Motorola	Circular or Rho/Theta optional Pulse Comp.	Approximately Ten Time Shared	10 m to 37 km LOS	5.4-5.6 or 9.3-9.5 GHz	115/230 VAC 50-400 Hz or 24-30 VDC optional	24-30 VDC	400 W
TELLUROMETER Plessy, Incorporated	Circular Phase Comp.	Three Time Shared	50 m to 250 km LOS	2.8-3.3 GHz	12 VDC	10.5-14 VDC	200 mW
TRISPONDER (202) Del Norte Technology, Incorporated	Circular Phase Comp.	Four Time Shared	100 m to 80 km LOS	9.3-9.5 GHz	22-32 VDC	22-32 VDC	1000 W

TABLE 2-4

SHORT-RANGE RADIODETERMINATION SYSTEMS CHARACTERISTICS
(2 of 3)

SYSTEM	VOLUME (m³)		WEIGHT (kg)		EQUIPMENT TRAINING	REPAIR PHILOSOPHY
	MOBILE (a)	BASE (b)	MOBILE (a)	BASE (b)		
AUTOTAPE	0.01	0.10	28	22	Arrange with manufacturer	PCB exchange Some interchangeable parts
MINIRAN	0.02	0.03	27	7	Arrange with manufacturer	PCB exchange Some interchangeable parts
MINIRANGER III	0.03	0.01	16.8	2.3	Operator and maintenance course at manufacturer	Repair kit PCB exchange
TELLUROMETER	0.03	0.03	16	15	Arrange with manufacturer	PCB exchange Module exchange Component replacement
TRISPONDER	0.04	0.01	35	10	2-3 day course at manufacturer	PCB exchange Some interchangeable parts

(a) Not including antenna

(b) Per station, not including antenna

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TABLE 2-4

SHORT-RANGE RADIODETERMINATION SYSTEM CHARACTERISTICS
(3 of 3)

SYSTEM	APPROXIMATE COST	ACCURACY	FEATURES
AUTOTAPE	$125,000 3-range system	4.0 m one-sigma position accuracy per R&DC evaluation (two LOP's)	Nixie Tube range displays, 20-line serial output for each, 2 or 3 ranges (DM-40 or DM-43), complete preventive maintenance program, integral voice communications from mobile to base, go/no-go indication
MINIRAN	$35,000 2-range system	+2 m @ 45 km ranging accuracy per manufacturer specifications (per LOP)	Gas discharge display of both ranges, rack mountable, parallel BCD data output, event number selection
MINIRANGER III	$35,000 2-range system	11 m one-sigma position accuracy per R&DC evaluation (two LOP's)	LED display of two ranges, rack mountable, BDC data output, automatic shutdown of shore units after last interrogation, built-in test evaluation variable display update interval, extensive options
TELLUROMETER	$90,000 3-range system	+1.5 m ranging accuracy per manufacturer specifications (per LOP)	Nixie tube display, high rate of display update, parallel BCD data output, Hp 9800 interface, duplex voice communcation between units, display hold, signal loss light, mobile/base units interchangeable
TRISPONDER	$30,000 2-range system	3 m @ 80 km ranging accuracy per manufacturer specifications (per LOP)	Strobed BCD data output, waterproof transit cases, established preventive maintenance program, display test, remote on/off

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TABLE 2-5

MEDIUM-RANGE RADIODETERMINATION SYSTEMS CHARACTERISTICS

(1 of 3)

SYSTEM & MANUFACTURER	OPERATING MODES	NUMBER OF USERS	OPERATING RANGE	OPERATING FREQUENCY	SUPPLY VOLTAGE		MAXIMUM RF POWER
					MOBILE	BASE	
ARGO Cubic Western Data Corporation	Circular or Hyperbolic Phase Comp.	2-range: 12 3-range: 9 4-range: 7 Hyperbolic: unlimited	1-740 km	1.6 MHz to 2.0 MHz	24 VDC or 115/230 VAC 50-60 Hz	22-32 VDC	100 W PEP
MAXIRAN Navigation Management, Incorporated	Circular Phase Comp.	Eight	0-240 km (minimum)	420 to 450 MHz	12 VDC or 110 VAC 50-400 Hz	12 VDC	200 W PEP (minimum)
RAYDIST-T Teledyne Hastings-Raydist	Hyperbolic Phase Comp.	Unlimited	0.18 times baseline length to 480 km	Mobile: 1.6 MHz Base: 3.2 MHz	24 VDC (converted from 115 VAC)	24 VDC (converted from 115 VAC)	Base: 70 W PEP Mobile: 40 W PEP

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TABLE 2-5

MEDIUM-RANGE RADIODETERMINATION SYSTEMS CHARACTERISTICS
(2 of 3)

SYSTEM	VOLUME (m³)		WEIGHT (kg)		TRAINING	REPAIR PHILOSOPHY
	MOBILE (a)	BASE (b)	MOBILE (a)	BASE (b)		
ARGO	0.20	0.20	41	28	Two weeks at MFR, one week on site	PCB exchange Some interchangeable parts
MAXIRAN	0.10	0.03	50	18	Arrange with MFR	PCB exchange Some interchangeable parts
RAYDIST-T	0.10	0.03	30	13	One week at MFR	Module and subassembly replacement Repair at MFR

(a) Not including antenna

(b) Per station, not including antenna

TABLE 2-5

MEDIUM-RANGE RADIODETERMINATION SYSTEM CHARACTERISTICS
(3 of 3)

SYSTEM	APPROXIMATE COST	ACCURACY	FEATURES
ARGO	$150,000 3-range system	Approximately 10-20m position accuracy based on average installations (three LOP's)	Rack mountable, 24-hour clock, analog data output, 5-minute warmup, fault isolation techniques incorporated, go/no-go indication, 4-channel display, several condition alarms
MAXIRAN	$76,000 3-range system	3m ranging accuracy @ 80 km per MFR specifications. Estimate 10-20 meters position accuracy based on limited test information. (three LOP's)	Employs correlation techniques and surface acoustic wave devices to enhance system gain, CRT display, 3-range gas discharge display, event counter 24-hour clock, both parallel and serial BCD data outputs, transponders waterproof, designed to interface with selectable level power amplifier for increased range, non-ambiguous LOP's
RAYDIST-T	$80,000 3-range system	$\pm$3m position accuracy @ 65 km per MFR specifications. Estimate 10-20 meters actual position accuracy based on known test data (three LOP's)	Family of cooperative systems allows wide choice of operating modes, two ranges displayed on rotating dials, analog data output, fault isolation techniques incorporated

2.5 Satellite Methods

2.5.1 Introduction

Satellite positioning and navigation methods, like several other methods discussed in this report, are new and developing. In fact, it is just ten years since the world's first world-wide satellite navigation system was made available for commercial use. But in that short time, great advances have been made. So much so, that this form of navigation is presently being considered by the U.S. Government as "the system" to end the proliferation of U.S. navigation systems, presently in use or planned. A satellite system which is now in development may make all surface navigation systems redundant, with the possible exception of precision short-range systems such as aircraft instrument landing systems. That, however, is in the future.

At present there is only one world-wide satellite navigation system in operation. This system, which is maintained by the U.S. Navy, provides periodic navigation information which is useful not only to navigators but also to geodetic and hydrographic surveyors. Present applications include absolute position reference, calibration of localized reference systems, extension of on-shore control to off-shore applications, relative position grid development and marine navigation. In the following paragraphs, the present and future satellite navigation systems are described and their possible applications to buoy placement operations are discussed.

2.5.2 History

In 1957 the U.S.S.R. launched the world's first satellite, SPUTNIK I, into orbit around the earth. Its telemetry data were monitored by scientists at the Applied Physics Laboratory (APL) of John Hopkins University, where it was discovered that the doppler shifts of the radio telemetry signals could be detected in such a manner as to provide position information for the orbiting satellite. In fact, this could be done with an astounding accuracy (for that time) of about 150 meters.

If doppler measurements taken at a terrestial point could be used to determine the position of a satellite in space, then it also seemed likely to the APL scientists that the reverse might be feasible, i.e., a terrestial point could be "fixed" using doppler measurements of signals transmitted by the satellite from a known position. It was this concept which led to the development of the first satellite navigation system by the United States.

The Navy had become aware of the work at APL and in December 1958 awarded APL an R&D contract for an ambitious satellite program. The object of this program was to apply APL's doppler navigation concepts to an accurate global navigation system that could be used by the Polaris ballistic missile submarines. The first satellite went into orbit in April 1960 and by 1964 the complete system of six satellites was in orbit and the Navy Navigation Satellite System (NNSS) was in operation for military use.

The NNSS, most commonly referred to as TRANSIT, remained purely a military system until 1967. At that time, the system's details were released to commercial industry so that public user equipment could be developed and marketed. This equipment is now available from manufacturers in several countries, including France, Great Britain, Canada, Japan, and the United States, and is in world-wide use. Notable user countries include the U.S.S.R. and the Peoples Republic of China (12).

Lack of high dynamic accuracy and continuous fix capabilities are two shortcomings of TRANSIT. These and other limitations have provided some of the impetus for development of a next generation system. Two programs, the Navy's TIMATION and the Air Force's 621B, were begun in 1964. These programs individually developed, tested, and proved new theories and improved equipments, but neither effort resulted in a fully operational system.

In 1970 work began on a review of all navigation systems to relate them to each other according to cost and need. The work, which was approved in January and updated in December 1973, called for a reduction in the number of DOD-funded navigation systems in order to reduce costs. During this same period, other work was undertaken to show the merits of satellite navigation systems, resulting in an April 1973 decision by the Defense Systems Acquisition Review Council (DSARC) to develop a single Defense Navigation Satellite System. The Air Force was assigned as the executive agency for this joint military operation.

In November 1973 the system was entitled the NAVSTAR Global Positioning System (GPS). The best features of the TIMATION and 621B programs were combined to form the basis for the development of a system that will eventually provide continuous world-wide navigation in three dimensions with an accuracy which has not been previously obtainable in dynamic situations.

In the summer of 1977 the first GPS satellite was placed in orbit. Twenty-three others are to follow until full operational capability is achieved by the mid-to-late 1980's.

2.5.3 Signal Propagation Considerations

As frequency increases, air becomes more transparent to radio-wave energy. This results in reduced power requirements versus effective atmospheric range and allows for radio wave propagation through the inosphere/troposphere interface. This characteristic and its effects are important considerations for satellite-to-earth-to-satellite communications. Obviously, the signal must be capable of transiting the air layer boundaries, but in addition to that, out of necessity, it must do it at low power levels. Satellites are usually capable of producing only a small amount of electrical power (generally from converting solar energy). The TRANSIT satellites, for example, produce only about 25 watts of power, thereby limiting the power available for signal transmission, which in this case is 1.5 watts. With these and other considerations to account for, TRANSIT and NAVSTAR operate on VHF/UHF and UHF frequencies respectively. However, even at these frequences both the ionosphere and the troposphere significantly affect signal propagation.

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The error budget for GPS, which is shown in Table 2-6, shows that approximately 55 percent of the system error is attributable to signal propagation uncertainties when a single transmission frequency format is used. This percentage drops to 19 percent for a dual transmission frequency format, but nevertheless this is still a significant factor which will affect navigational accuracy.

As the radio-wave signals pass from the satellite to the receiver, they are first refracted by the ionosphere and then by the troposphere. The refraction effects are different in both regions as are the methods for correcting/compensating for them. Ionospheric refraction is a function of the electron density, signal frequency, and the ray-path through it. The electron density is strongly affected by solar cycles, diurnal effects and geomagnetic latitude. The propagation velocity of the signal decreases as the frequency decreases. Path-related effects are in part dependent upon the mean ionospheric height. Tropospheric refraction, which is also a function of the ray-path, is primarily affected by water vapor content and practically independent of frequency.

A method based on the frequency dependence can be employed to correct for ionospheric refraction effects. Although propagation effects can not be predicted for a given point in time and space, the relationship that exists between the effects observed at different frequencies allows for a highly reliable empirical determination to be made.

Frequency diversity does not allow for determination of refraction in the troposphere though because as stated, there is practically no frequency-related effect. Instead, a compensating method that is common to many other radio navigation systems is employed in satellite navigation. Processing of the signals includes the application of a mathematical model of the troposphere to mitigate its refraction effects. Since the troposphere is continually changing in a manner which is only partially predictable, application of the model only serves to minimize rather than eliminate position errors resulting from tropospheric refraction.

2.5.4 Description of the Navy Navigation Satellite System (TRANSIT)

TRANSIT provides a world-wide, 24-hours-per-day, all-weather navigation and positioning system. Common uses of the system are for land positioning and surveying, offshore positioning and marine navigation. There is no limit to the number of users that can operate with the system at any one time.

The space segment of TRANSIT is composed of a constellation of six satellites that have been placed into 108-minute duration polar orbits at a nominal 1100 kilometers above the earth. Approximately a dozen more satellites are in reserve to replace operational ones that malfunction. The predicted useful lifetime of each satellite is four years, however, the ones in the present group have been in orbit from four to ten years. One of the six has been exhibiting some operating problems and is presently declared unserviceable by the Navy. It has not been learned whether or not a replacement satellite has been scheduled for insertion.

The ground segment of the TRANSIT system is composed of four tracking stations located in Hawaii, Maine, Minnesota, and California, two injections stations, a computing/command center and the U.S. Naval Astronautics group. The tracking stations collect data concerning the past performance of every satellite. This information is transmitted to the controlling station, Point Magu, California, where a computations facility predicts future orbit parameters for the satellites. This information is then passed to injection stations which transmit the information to the satellites for updating the navigation message to be continuously broadcasted by the satellites.

In order to determine a fix, a user equipment must decode and extract the satellite message, measure and collect satellite velocities through integration of doppler counts and combine the doppler data with the satellite coordinates in order to obtain a computed antenna position at the time of the observation. A curve of the apparent shift in frequency due to the doppler effect, taken at several points in time, describes the user's unique location.

Users of TRANSIT must deal with several limitations and error sources. Some of the more important ones are listed below:

a. Infrequent satellite passes

b. Overlapping passes and co-interference

c. Geometrical effects on errors

d. Propagation anomolies

e. Coordinate transformations

f. Geoidal height variations

g. Velocity considerations

h. User equipment capability

Fixes are available at a near hourly rate in the middle latitudes, varying from less than one-half hour at the poles to about two hours at the equator. The fix availability can only be increased by adding to the number of satellites in orbit, however, this is not a practical option of the TRANSIT system.

TRANSIT user equipment automatically listens to the operating frequency and scans a certain range of doppler frequencies. The first satellite to appear over the radio horizon is locked onto and tracked. A following satellite can not be tracked until the first one has passed. This can become a drawback when the equipment is unattended and the first satellite is not useful for some reason, but the next one is. Useful information is lost with the most notable result being the further spreading out of the time interval between useful passes. This drawback can be dealt with by manual tuning, which is satisfactory for navigation or point positioning surveys, but adds an additional operational factor to translocation surveying; both receiving sets have to be

simultaneously (not instantaneously) retuned manually. This could require additional survey personnel.

Another phenomena of overlapping satellite passes is that on periodic occasions the doppler frequency for two satellites can be identical. This can thoroughly confuse the user equipment and cause unusable results. The only remedial action for this situation is to completely ignore passes that involve this system anomoly.

The effect on errors due to geometry is a function of a satellite's elevation angle (angle formed at observer by imaginary lines between him and the horizon and satellite). Fix accuracy seriously degrades for elevation angles approaching 0 and 90 degrees. For this reason, it is common practice not to accept data when the elevation angle is less than 15 degrees or more than 70 degrees.

Coordinate transformation is a necessary function to be accounted for by the satellite surveyor (not always important for the navigator). Coordinate systems are described by a proliferation of geodetic datums and reference ellipsoids (a partial listing is contained in reference (14)). The datum used in TRANSIT is the World Geodetic System 1972 (WGS-72). The datum most commonly used in the United States and Canada is the North American Datum 1927 (NAD27). In addition to the major systems, local and regional coordinate systems are used by different organizations (even these vary from area to area within single agencies). There are methods to equate (or transform) most all of the different datums, so the user need only be aware of the datums (coordinate systems) that he is working with in order to make appropriate corrections to his survey data. Of course, coordinates of a WGS-72 survey can be easily tied directly to NAD27 simply by making a TRANSIT survey of a point which has been previously surveyed using NAD27 datum.

Velocity considerations are a concern of the navigator and not generally applicable to the surveyor. This is simply because the navigator is generally in motion and the surveyor is fixed in position. Recall that the doppler effect resulted from the relative motion between the signal source and observer. If both are moving, doppler interpretation becomes more complex, though not greatly so. The limiting factor in accurate position determination is not the velocity of the satellite, for it is well known, but the velocity of the observer, which is not always accurately known. One-tenth of a knot velocity error is sufficient to cause a position error of from 50 to 100 meters (15).

User equipment capability warrants little discussion here. Either it is composed of the best state-of-the-art equipment and employs the latest software improvements or it does not. The proof is in demonstrated accuracy. As the reader is now aware, less accurate equipment is or may be suitable for general navigation, whereas only the most accurate equipment is acceptable for surveying.

TRANSIT characteristics are summarized in Table 2-6.

2.5.5 Principles of TRANSIT Satellite Navigation

The doppler shift, or apparent change in frequency of a stable source caused by relative motion between the observer and source, is used in the TRANSIT satellite system to determine both the satellite orbit parameters and user locations. In order to understand the doppler shift effect, one might consider the effect noticed by an observer of a train whistle while the train is in motion. The tone of the whistle varies as the train moves with respect to the observer and is especially noted as the train passes him. Another observer at another location would also hear the same sound, but a curve of the change of tone (dopper shift curve) would be different for the observers' locations at the same instant of time. The fact that the two curves are different allows for either of two determinations to be made; if an observer had knowledge of his position, he could determine the location of the track, or conversely he could determine his own position if he knew the location of the track. Substituting satellite for train and orbit for track is one way to visualize the basic principle of doppler satellite navigation.

Each of the satellites, which have been placed into prescribed earth orbits, contains a precision frequency source, a receiver, a transmitter, and a memory. At prescribed intervals, the satellite receiver receives a message from a ground station. This message, which contains a prediction of the satellite's orbit until the next update time, is stored in memory. The precision frequency source is used to develop the precise satellite transmitting frequency(ies) which is/are transmitted as a continuous wave transmission. At precise intervals (two minutes, for example), the information in memory, which includes the navigation message and other satellite identification and sync information, is modulated on the continuously transmitted carrier.

The sole function of the ground network is to track the satellites in order to make corrections to their future orbit predictions. In order to do this, it is necessary to have past-orbit information. The precisely located ground stations track every pass that every satellite makes in order to obtain a record of the doppler shifts. All of this information is then processed at the controlling ground station and compared with previous data. The new orbit prediction is then made, encoded, and uploaded into (transmitted to) the satellites by one or more injection stations. This is the navigation message mentioned above.

User equipment is comprised of three basic components, a receiving system, a data processor/display and a software package. Since the signal power of the satellite is very low, the receiver is ultra-sensitive and employs a phase-locked loop which enhances signal reception. It also employs a demodulator and an oscillator of good short-term stability. Long-term stability is not important, since the system is "clocked" by the highly stable satellite oscillator (e.g., rubidium standard). The data processor can be a microprocessor or minicomputer depending upon the level of sophistication and desired accuracy. Software can be hardwired or externally entered, depending upon the facility, and can also vary in sophistication, depending upon the user's requirements.

When an orbiting TRANSIT satellite rises over the electrical horizon, its signal can be automatically acquired by a user's receiver. The

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satellite is then tracked until it disappears over the opposite horizon during which time the navigation message and doppler information is stored in computer memory. Integrated doppler counts are taken during several 2-minute intervals during the pass, with particular emphasis on data taken just before, at and right after the satellite's closest point of approach (CPA). This yields a succession of slant ranges between the user's equipment and points along the satellite's path. After all data has accumulated for a single pass, the computer takes the user's assumed position and determines the doppler curve for that location based upon the orbital parameters transmitted by the tracked satellite. This curve is then compared by use of an iterative least square method with the computed curve based on received doppler data, i.e., the two curves are compared and if they differ, the assumed position is automatically revised and a new curve is computed and compared. The comparison process continues until such time as convergence occurs. Convergence is reached when the curve of a successive position assumption differs from the received curve by only a small amount (e.g., a few centimeters). This information is then outputted to the navigator who notes his position and then dead-reckons until the next satellite fix is available.

2.5.6 Principles of TRANSIT Satellite Surveying

TRANSIT can also be used for surveying operations. The same satellite information is used, but the user equipment and operating procedures are changed.

Navigation systems in general can tolerate a moderate amount of errors, but the nature of survey work requires that all possible errors be eliminated or compensated for in some manner. The satellite surveyor must reckon with all of the following:

    a.   Equipment inaccuracies

    b.   Insufficient and assymetrically distributed doppler data

    c.   Orbit uncertainties

    d.   Antenna height errors

    e.   Refraction errors

In addition, these factors must be taken into consideration:

    a.   The time available for the survey operation

    b.   The degree of accuracy required

    c.   Access to the "precise ephemeris" (discussed later)

The answers to these three considerations will affect the degree of necessity to deal with the system errors and likewise the capability to deal with the errors will impact these considerations. The errors and their remedies will be discussed first:

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Equipment Inaccuracies - There are two primary forms of equipment errors which affect surveying accuracy, random doppler count errors and rounding-off errors caused by computer truncation. The remedy to the latter problem is to simply increase the computer's capacity. The remedy to the former is also rather simple; in theory at least. There are two sources of random doppler count errors, the stability of the oscillator (in the user's receiver) and message decoder phase jitter errors caused by multi-path signal reception. Oscillator-induced errors can be reduced by using an oscillator that exhibits good short-term stability. Phase jitter increases as signal strength decreases, so errors can be reduced to a minimum by only accepting data when signal strength is of necessary level, e.g., only take data when the satellite is above a certain elevation.

Insufficient and Asymmetrically Distributed Doppler Data - Statisticians employ a time-honored method of reducing the effects of random errors in a system, and that is increasing the amount of data collected. The same applies here. It is also important that this data be symmetrical (13), meaning basically that consecutive doppler counts must all be valid (good) data and centered around the satellite's CPA.

Orbit Uncertainties - It follows that if the surveyor does not know precisely where the satellite is, he will not be able to determine his location. As noted earlier, the navigation satellite continuously broadcasts its ephemeris, or predicted position. The actual position of the satellite will vary somewhat due to a number of factors, including the effects of the earth's non-uniform gravitational field. It is the function of the ground network to develop the best possible orbit prediction.

Antenna Height Errors - Satellite position location results from a three-dimensional solution of a succession of integrated doppler counts (the integral of the doppler count, or frequency shift, yields a slant range difference between the transmitter and an observer, therefore, the altitude, or Z-axis, must be considered in addition to the X&Y horizontal axes. Antenna height is described in terms of a reference spheroid and the actual earth radius at the survey site. The difference between the two is called the geoidal height and must be added to the sea level height which the surveyor can obtain from a barometer or by other methods.

Refraction Errors - The effect of ionospheric and tropospheric refraction is to vary the electrical path length between the satellite and user's receiver resulting in an offset as compared to the actual path length. Methods of dealing with this form of error were discussed in Subsection 2.5.3. As a reminder, ionospheric refraction can be eliminated completely by using a frequency deversity method, and tropospheric refraction can be mitigated by using a model of its mean effects in order to adjust actual path length measurements.

With knowledge of the above group of errors, the surveyor must make a decision about his survey approach. His decision must take into account one or the other (or both) of two important factors, time and funds. If he has a lot of time and little funds, then he should pursue a survey method of "point positioning." If he has little time and sufficient funds or just plain sufficient

funds, he should pursue the "translocation" survey method. Of course there are many other considerations to be made, but these two are basically the most important.

The same survey accuracy is obtainable by either the translocation or point positioning methods. The time required for the survey is the distinguishing factor.

Point Positioning - The ingredients for a good point positioning survey are a dual frequency receiver, about 150 satellite passes, a good software package, access to a computer, access to the "precise ephemeris" and lots of time (30-plus days). Frequency diversity is used to resolve ionospheric refraction, a large number of satellite passes permits random errors averaging to minimize outlyers, the software package should include all the latest proven mathematical models of the troposphere, geometric error effects, reference spheroid, etc. A computer is essential to data reduction. Access to the precise ephemeris is probably the single most important requirement (although it is difficult to consider any of the other factors as being less important). A single-frequency receiver, like those common to navigation sets, can be used for surveying, but although the results could be better than that obtained during navigation exercises, it can not provide the accuracy prevalent in a dual-frequency receiver system.

As noted earlier, ground stations are used to determine precisely where a satellite has been. With present technology, this can be done to an accuracy of centimeters or better. This information is used to predict future orbit parameters, or ephemeris. The information which was collected in order to predict the future orbits is, in fact, the basis for development of the "precise ephemeris," the past location of the satellite with respect to time and space. A surveyor must process his data with the precise ephemeris in order to obtain the best possible accuracy that can be provided by the system.

Translocation - The translocation method is a recent advancement to the art of satellite surveying. Its development resulted from analysis of data collected from single satellite passes by two receivers placed at different geographical locations. The analysis showed that some of the system's errors and error effects were correlated, including some of those associated with ephemeris, GDOP, and refraction. Removal of the correlated errors resulted in a co-location relative accuracy that was an order of magnitude better than position fixing using only a small number of passes. And, since the correlation could be rapidly determined, the era of the one day or less, highly accurate satellite survey was at hand. A surveyor need only place one receiver over a known location (previous survey by satellite or conventional method), locate another receiver at the point to be surveyed, collect simultaneous data for only a few passes and then reduce data to determine the location of the surveyed point with an accuracy that could possibly challenge the accuracy of the reference site's original survey.

When translocation is desired/necessary for surveying an area which is void of reference survey marks, the satellite system is used to point locate the reference site. In this case the aforementioned 150 passes would be necessary to establish survey quality control, thereby possibly making the

operation a bit time consuming. However, while the point data is being collected, several translocated sites could be surveyed by using the very same data being collected for point location. In the event that several sites, let us say ten or so, require locating, the point positioning time loss is recovered. When only surveying a few sites, this would not be completely the case.

There is a limitation of how far the two translocation sites may be separated. This is because of two reasons. One is that the satellite will not be visible to the two points for a long enough period to obtain simultaneous data. The other reasons has to do with the changed geometry of the arc described by the satellite as viewed from different locations.

A primary advantage of translocation is that no access is required to the precise ephemeris (kept by the controlling agency) because in effect (though not exactly), precise ephemeris results from the translocation procedure. This is important because precise ephemeris is not commercially available for the Navy Navigation Satellite System.

TRANSIT satellite surveying, both by point positioning and translocation, can provide extremely good results when properly conducted.

2.5.7 Description of the NAVSTAR Global Positioning System (GPS)

The NAVSTAR (NAVigation System using Timing And Ranging) Global Positioning System (GPS) is designed to replace TRANSIT and certain other navigation systems. Its implementation is designed to produce a two-fold result: stopping the proliferation of DOD-sponsored radio aids to navigation and providing a world-wide, all-weather, continuously available navigation system capable of high dynamic accuracy.

GPS will consist of a constellation of satellites, a master control station, four tracking stations (including one at master control), an upload station (also at master control), and an unlimited number of users. The satellites will broadcast navigation information continuously so that any user located in any part of the world will be able to compute near-real-time fixes at any time. In addition, time dissemination accurate to fractions of microseconds will be made available. The Department of Defense expects to have 25,000 to 30,000 users in almost every military mission area.

A total of 24 satellites, 8 in each of three circular planes and approximately 20,000 kilometers in radius, will comprise the space segment. This will ensure that at least six satellites will be "visible" at any given location and time. The first of these satellites was launched in the summer of 1977. By 1981, 9-11 satellites are to be in orbit, providing periodic precise three-dimensional and continuous coarse two-dimensional capability.

Four monitor stations will be installed. They will be located at Elmendorf AFB, Alaska; Anderson AFB, Guam; Wahiawa, Hawaii; and Vandenburg AFB, California. Vandenburg will also serve as master control and upload stations.

User equipment development is presently under contract to DOD. The initial user sets will be used exclusively for tests and evaluation by the DOD and DOD-contracted agencies. Present contracts are for six classes of equipment which are for high accuracy, medium dynamics of user; high accuracy, high dynamics of user; medium accuracy, medium dynamics of user (low cost); high accuracy, low dynamics of user; a manpack; and submarine applications. The GPS user equipment will be quite different from TRANSIT equipment. In addition to the different frequencies, signal structure and modulation methods, the outstanding differences between the systems are that GPS operates on three or four satellite signals simultaneously as compared to one for TRANSIT, and the ranging method is one of "pseudo-ranging" for GPS whereas TRANSIT operates on doppler information.

The basis of GPS ranging is that the satellites transmit time ticks with a "tag" which indicates the time it was transmitted. The user equipment determines ranges to the satellites by measuring the difference between the time that the signal (tick) is transmitted and the time that it is received (distance equals time multiplied by signal propagation velocity). If this is done for three satellites (three lines adequately define a point), a position is described which is in error by the amount proportional to the difference between the user and satellite clocks. Time can be solved by ranging on one additional satellite (4 equations, 4 unknowns, X, Y & Z coordinates and time). Since each signal contains a time-bias error, the individually determined ranges are called pseudo-ranges.

As GPS is primarily intended for military/government usage, a great deal of effort has been directed toward reducing the possibility of sabotage (jamming) and making the full use of the system available only to "friendlies." The unclassified mechanics of the security measures will not be discussed here, but suffice to say, the transmitted signal structure is quite complicated.

GPS characteristics are listed in Table 2-7.

2.5.8 TRANSIT and GPS User Equipment

TRANSIT user equipment manufacturers market either navigation or survey sets or both. Navigation sets are typically capable of single-frequency operation and less accuracy than the survey sets. They are often times designed to be used as one sensor in a larger navigation system. Survey sets are stand-alone and can provide excellent accuracy. Characteristics of a cross section of both navigation and survey equipments, as provided by their manufacturers, are contained in Tables 2-8 and 2-9, respectively. Selection of the equipments for presentation was based solely on availability of information. Individual costs are not listed in the tables, because extensive options are available for most systems. Acqusition costs range from about $15K for a simple navigation set to around $150K for a complete translocation survey system.

GPS user equipments are presently under development. A summary of the design objectives of several development contracts are contained in Table 2-10.

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2.5.9 Accuracy Considerations

In the past sections, all TRANSIT system errors of any consequence have been identified and discussed with regard to their effects and the methods employed to compensate for them, therefore, they will not be reiterated here. GPS errors, with exception of multipath errors, have likewise been discussed. A summary of both systems' errors are contained in Table 2-11. A GPS multipath discussion follows:

As a signal transits the distance between the satellite and ground equipment, it might be dispersed by the effects of atmospheric conditions, e.g., reflected or refracted by a dense atmospheric layer. At the ground equipment, the detected signal is a composite of the energy received from the direct path and all other paths caused by reflection and re-reflection (including refraction effects). Depending upon the phase of the reflected signal energy, it will tend to be destructive or non-destructive to the direct path energy. The result of this phenomena is that a phase jitter will be generated in the ground equipment's detector. The reader might visualize this effect by considering the effect on a television picture when an airplane passes through its reception path. The picture is seen to fade in and out and "ghosts" are seen to jitter across the screen, all because some of the energy is being reflected from the aircraft. In satellite navigation systems (as well as other types), the phase jitter translates to errors in position which are termed multipath errors.

The GPS will employ several methods to mitigate multipath errors. One of them is the same as for the TRANSIT system; rejection of data received from satellites at very high or very low elevation angles. Other methods are use of a high frequency data code with good correlation properties, transmission in the L-Band where reflections are usually diffuse, and rejection by antenna gain pattern and circular polarization.

Present predictions are that GPS will provide instantaneous three-dimensional fix accuracy of about 13 meters, two-sigma (8 meters in the horizontal plane), when dual-frequency four satellite reception techniques are observed. Accuracy predictions have become better as the GPS program has developed and improved error reduction techniques have been developed. The final result may be that the system will provide better accuracy than that presently projected.

TRANSIT accuracy has also improved as a result of improved techniques. As an example, the accuracy of orbital determination has been increased to about 5-10 meters by using the WGS-72 geopotential model. The system's initial model, APL 1.0, provided only 100-150 meters accuracy. The system's total error budget is now 15-30 meters. Typical single-pass solution errors for navigation sets range from about 100 to 300 meters and up to about 50 meters for survey sets. Multiple-pass solutions and translocation methods can reduce the total fix error to 1-5 meters (translocation referenced to a known location; multiple-pass point positioning relative to WGS-72).

Operator errors are projected to be minimal for GPS, because the entire data collection, reduction and printout will be fully automated. This method is also employed in TRANSIT navigation sets, but not necessarily

with point positioning or not at all with translocation survey equipments. In those cases, data handling errors are possible. Care must be taken to ensure that operator entries to data reduction programs are proper.

2.5.10 Potential Application to Buoy Tending

Satellite survey will have the potential to satisfy buoy-tending requirements in another decade. As for the present, the potential is there, but applications are limited. Present-day TRANSIT provides only a periodic fix capability and is better suited to static surveying than to dynamic position determination.

TRANSIT satellite survey methods can provide a relative accuracy of approximately one meter (can be relative to a known absolute position) and an absolute accuracy (WGS-72 coordinates) of five meters or better. This accuracy can be applied to buoy-placement operations in an indirect manner. Earlier in this report (Subsection 2.2.10), optical methods were identified as being useful to buoy tending, providing that a sufficient number of surveyed stations were available to buoy tender personnel. It is often the case, however, that sufficient stations are not available. In that instance, stations could be surveyed by satellite methods, as well as a number of conventional methods.

Conventional survey methods are undoubtedly the least expensive and potentially the most accurate to locate a new point referenced to an easily accessible local control reference point. However, there are numerous areas in which local reference is not easily accessible. In addition, local control could be referenced to a variety of datums and not necessarily to NAD27. Satellite surveying with the TRANSIT system could offer a cost-effective survey of sufficient accuracy to deal with either of these two circumstances.

The projected applications of GPS are practically limitless, including dynamic buoy-tending operations. The availability of accurate, instantaneous near-real-time fixes could feasibly make a GPS user set the only navigation set required by a buoy tender by the end of the next decade.

2.5.11 Safety Considerations

There are no unusual safety precautions to be considered when using either TRANSIT or GPS user equipment. Some equipments are designed to be completely hands-off. Other equipment require only the manipulation of a few equipment-face controls or data entry from toggles or a data terminal. Maintenance personnel can be exposed to normal AC supply and logic level DC voltages, neither of which are unusual.

2.5.12 Conclusions

The NAVSTAR Global Positioning System, which is in process of development, is projected to be available for military/government users in two stages. The first stage is scheduled to be completed by 1981, and will offer continuous horizontal fixing capability with an accuracy of about 50 meters. More accurate three-dimensional fixing will also be available on a periodic

basis. Complete continuous three-dimensional coverage, with a expected accuracy
of approximately 13 meters, two-sigma, is expected by 1984. The interim capa-
bility 1981-1984 is not sufficient for buoy placement, but the projected opera-
tional capability for 1984 and onward is.

Although GPS is not expected to be fully operational until
1984 (most knowledgeable people consider that to be overly optimistic and that
1988-1990 is more likely), it is important for the Coast Guard to keep abreast
of the system development. User equipment is being developed under six DOD
contracts to satisfy the requirements that have already been defined by various
user agencies. It is doubtful, however, that any of the six equipments being
developed will be useful for buoy tending without the addition of input/output
information and equipment such as a specialized display that suits buoy-placement
situations. The executive agency for GPS, the U.S. Air Force, has established a
GPS Joint Program Office (JPO) at its Space and Missile Systems Organization
(SAMSO) office in Los Angeles, to deal with the individual requirements of other
government agencies. The R&D Center encourages adequate preparation by Coast
Guard Headquarters so that a Coast Guard-defined GPS user equipment will be
available when the space segment of GPS is fully operational.

TRANSIT is not useful for dynamic positioning, thereby
eliminating it from consideration for buoy-placement use. However, the system,
coupled with proper user equipment, provides the capability of one-meter relative
accuracy when used in a static mode. This makes it potentially useful for
surveying reference stations for use with optical sighting equipment. Since
optical sighting methods are known to be capable of providing excellent position-
ing results, an abundance of reference stations could be very useful. There
are many instances where satellite surveying could aid this effort in a cost-
effective manner, e.g., remote and other areas where local control is not
available or adequate. Conventional methods of survey would generally be less
costly to conduct on an individual site basis, but an overall cost saving can
be realized if TRANSIT translocation equipment is efficiently used by Coast
Guard personnel as compared to a succession of contracted surveys.

TABLE 2-6

CHARACTERISTICS OF THE NAVY NAVIGATION SATELLITE SYSTEM

Coverage: World-Wide

Availability: 24 hours per day

Number of possible users: Unlimited

Satellites

    Quantity: Six (one presently inoperative)
    Type of orbit: Circular, polar
    Period of orbit: 108 minutes
    Altitude of orbit: 1100 kilometers (nominal)

Satellite Transmissions

    Frequency: 150 and 400 MHz
    Type of emission: CW, phase modulated
    Data interval: 2 minutes
    Data transmitted: Fixed orbital parameters, variable
                  orbital parameters, time and sync
                  marks

    Update interval for variable data: 12-16 hours

Fix availability: Hourly at middle latitudes

Method of fixing: Measure doppler data and combine with
                  satellite coordinates to compute
                  location at time of observation

Datum: WGS-72

Operating Agency: U.S. Navy (Astronautics Group)

Number of tracking stations: Four

Number of injection stations: Two

System Accuracy: 15-30 meters, RSS

Application Accuracy

    Translocation: 1-5 meters, RMS (relative to known point)
    Point positioning: 5 meters, RMS (relative to WGS-72)
    Navigation: 100-300 meters, RMS (relative to WGS-72)

TABLE 2-7

CHARACTERISTICS OF NAVSTAR GLOBAL POSITIONING SYSTEM

Coverage:	World-Wide
Availability:	24 hours per day
Number of possible users:	Unlimited

Satellites

Quantity:	24
Type of orbit:	Circular; eight in each of three planes
Period of orbit:	12 hours
Altitude of orbit:	19,260 kilometers

Satellite Transmissions

Frequency:	1227.6 and 1575.42 MHz
Type of emission:	Multiplex
Data interval:	30 seconds
Data transmission:	Secure and clear acquisition code, fixed orbital parameters, variable orbital parameters, time correlated binary data stream, sync and time information

Fix availability:	Continuous
Method of fixing:	Pseudo-ranging to four satellites simultaneously; three for X,Y&Z position and the fourth to establish timing with time correlated binary data stream
Datum:	WGS-72
Operating Agency:	U.S. Air Force
Number of tracking stations:	Four
Number of injection stations:	One (co-located with one tracking station)
System accuracy (projected):	4-6 meters, RSS
Projected Application Accuracy; relative to WGS-72 using a four channel, dual frequency receiver:	13 meters, two-sigma, spherical 8 meters, two-sigma, radial

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TABLE 2-8

CHARACTERISTICS OF SELECTED TRANSIT NAVIGATION USER EQUIPMENT

CHARACTERISTIC	MAGNAVOX MX1102	NAVCOM 4800	NAVIDYNE ESZ-3000	TRACOR SATELLITE NAVIGATOR
Power:	100/115/208/230 ± 15% VAC, 45-66 Hz, 1ø,150 W max.	100/110/230 VAC,-20 to +15% VAC, 44-67 Hz, 1ø,95 W max.	105-230 VAC, 44-67 Hz, 1ø, 100 W max.	100-125 or 210-250 VAC, 50-60 Hz, 1ø,130 W max
Battery Backup:	10 minutes	30 minutes	10 minutes	None
Receiver Frequencies:	400 MHz	150 & 400 MHz	400 MHz	400 MHz
Receiver Sensitivity:	-145 dbm	-150 dbm	-150 dbm	-146 dbm
Tuning Method:	Automatic or Programmed	Automatic or Programed	Automatic	Automatic
Self Test:	Yes	No	No	No
Displays:	Approximately 20 Navigation and Satellite Information functions & self-diagnostic readout on LED display screen	Status lights for power, AGC lock, valid data, valid message, plus or minute re-refraction & hard copy nav. data	Status lights for power, AGC lock, valid data, valid message & hard copy nav. data	Latitude, longitude and GMT on LED's & status lights for message sync, RF lock and power
Receiver Size				
Height:	432 mm	304 mm	153 mm	363 mm
Width:	419 mm	483 mm	489 mm	317 mm
Depth:	356 mm	483 mm	483 mm	508 mm
Weight:	34 Kg	40 Kg	20 Kg	18 Kg
Antenna Size				
Height:	445 mm	152 mm	185 mm	610 mm
Diameter:	625 mm	432 mm	222 mm	76 mm
Weight:	4.1 Kg	3.6 Kg	1.8 Kg	3.6 Kg
Features:	Extensive display, simple operation, single-unit construction, programmed tracking, self-indicating malfunction testing, auto dead reckoning*	Hard-copy data, simple operation, 2 equipments in a single package, automatic dead reckoning*, self-check meter, dual frequency	Hard-copy data, simple operation, single-unit construction, auto dead reckoning*, encapsulated ant./pre-amp	LED displays, 2 units in a single package, automatic dead reckoning*
Options:	Automatic speed & heading input, remote monitor, printer, alarms	Remote display & recorder, alarms, integration with other nav. systems	Automatic speed & heading input, integration with other nav. systems	Automatic speed & heading input, remote display, alarm signals
Fix Accuracy: (WGS-72 datum)	100 meters + 400 meters per knot of user's speed error	Same as MX1102	Same as MX1102	200 meters + 400 meters per knot of user's speed error

*Manually entered user's speed and heading.

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TABLE 2-9

CHARACTERISTICS OF SELECTED TRANSIT SURVEY USER EQUIPMENT

CHARACTERISTICS	MAGNAVOX GEOCEIVER II	JMR INSTRUMENTS JMR-1
Power:	115/230 VAC, 1∅, 120 W maximum	12 VDC battery, 4.5 W average
Receiver Frequencies:	150 and 400 MHz	150 and 400 MHz
Receiver Sensitivity:	-145 dbm	-145 dbm
Oscillator Stability (2 minutes):	2×10^{-11}	6×10^{-12}
Tuning Method:	Manual and automatic	Manual and automatic
Self Test:	Yes	No
Displays:	Status lights for power, testing, RF lock and message reception and doppler frequency meter	Indicator lamps for power, RF lock and synchronization to satellite message
Receiver Size		
Height:	17.8 cm	38 cm
Width:	48.3 cm	22 cm
Depth:	50.8 cm	52 cm
Weight:	22.7 Kg	16 Kg
Antenna Size		
Height:	1.8 m	1 m (approximately)
Diameter:	1.0 m	0.5 m (approximate base diameter)
Weight:	8.2 Kg	P/O receiver weight
Carrying Provisions:	None	Handle or backpack
Shipping Containers:	Padded transit cases	Padded transit cases
Data Processing Requirements:	Teleprinter (Silent 700) Minicomputer (HP 21M20) Paper Tape Reader Software (available from Magnavox on paper tape)	Teleprinter (Silent 700) Minicomputer (JMR-1MP) Cassette Reader (JMR-1CRR) Software (available on cassettes from JMR)
Translocation Requirements:	Additional Receiver Additional Antenna Additional Software (available on paper tape from Magnavox)	Additional Receiver Additional Antenna Additional Software (available on cassettes from JMR) Additional 12 VDC battery
Training:	Factory and field training available at Magnavox	Factory and field training available at JMR
Data Reduction Site		
Point Positioning:	User's base or at company	User's base, at company, or on-site
Translocation:	User's base or at company	User's base or at company (on-site possible but not practical)
Accuracy		
Point Positioning (WGS-72):	Single Pass - 25 m Multi-Pass - 1 m	Single Pass - 25 m Multi-Pass - 1 to 2 m
Translocation (relative):	4-8 passes - 1 m 24 passes - less than 1 m	4-8 passes - 5 m 24 passes - 1 m
Comments:	Not designed for field transport. Requires AC generator for field use. Paper tape is difficult to handle. DC-operated field deployable set is in development at Magnavox. Training necessary.	Designed for field deployment. Requires 12 VDC batteries in field. Total weight for complete translocation set is approximately 100 Kg, including batteries. Training necessary.

TABLE 2-10

CHARACTERISTICS OF GPS USER EQUIPMENT DESIGN

CHARACTERISTIC	CLASS A	CLASS B	CLASS C	CLASS D	CLASS E	CLASS F
Design Accuracy:	10 m	10 m	100 m	10 m	10 m	10 m
Dynamics of User:	Medium	High	Medium	Low	Low	Low
Immunity to Jamming:	High	Medium	None	High	High	---
Miscellaneous Considerations:			Low Cost			Fast Lock
Applications:	Strategic Aircraft, Photo Recon.	Close Air Support, Surface Vessels	Mission Support, Surface Vessels, ASW, SAR	Land Vehicles, Surface Vessels to 40 kts	Manpack	Submarines
Projected Cost:	$30-35K	$25K	$10K	$25K	$15K	---
Development Contracts:	---	MRL (a) TI (b)	MRL	Collins (c)	MRL TI	---

(a) Magnavox Research Labs
(b) Texas Instruments, Inc.
(c) Collins Radio Company

TABLE 2-11

ERROR BUDGETS FOR GPS AND TRANSIT SATELLITE SYSTEMS

ERROR SOURCE	SINGLE FREQUENCY		DUAL FREQUENCY	
	TRANSIT	GPS	TRANSIT	GPS
Ephemeris:	10-15 m	1.5 m	10-15 m	1.5 m
Satellite Clock and Electronics:	3-6 m*	0.9 m	3-6 m*	0.9 m
Troposphere Model:	1.5 m	1.5 m	1.5 m	1.5 m
Ionosphere Model:	5 m	4.9 m	--	--
Receiver Noise:		1.5 m		2.4 m
Multipath:		1.2 m		1.8 m
Unmodeled Forces Acting on Satellite:	10-25 m		10-25 m	
TOTAL (RSS):	15.85 m to 30.47 m	5.75 m	14.53 m to 29.8 m	3.84 m

*Includes errors due to receiver noise and multipath.

2.6 Underwater Methods

2.6.1 Introduction

The ocean medium is more transparent to acoustic energy than
to any other form. For this reason, underwater acoustic instrumentation plays
an important part in all types of oceanographic work. The marine biologist,
for example, uses acoustic instrumentation to locate and study marine animals.
He might listen in on the noises that they generate, test their hearing response,
or observe schooling and migration patterns. Other oceanographers use underwater
acoustics for bottom profiling, navigation, or communications within the medium.

In recent years a great deal of commercial effort has been
expended to develop accurate underwater acoustic navigation and positioning
systems. Motivation for the effort has been largely provided by the rapidly
expanding offshore industries of petroleum and mining, both of which require
accurate positioning capability in deep ocean waters. The most useful system
which has been developed for this application is acoustic beacon navigation
systems. Travel to and from underwater locations and placement, inspection
and repairs of underwater equipment in most cases could not be as easily or
accurately done with any other positioning method.

There are many types of acoustic instrumentation, profilers,
sonars, depth finders, etc., but only underwater acoustic beacon navigation and
positioning systems will be herein analyzed for possible usefulness to buoy-
tending operations. Such systems can not only be used for underwater position-
ing, but they may also be used for surface positioning and navigation.

2.6.2 History

One of the earliest applications of underwater sound was the
installation of bells under light ships. The sound of the bells could be heard
by detection devices mounted on hulls of ships in the vicinity, allowing a form
of general location determination. In 1912, Thomas Fessenden developed an under-
water electrodynamic device which operated in the frequency range of 500-1000
Hz. The device, named the Fessenden oscillator, increased the range of under-
water signaling and made it possible for underwater communications by Morse
code.

During World War I, a system of underwater ranging was
developed. Dubbed ASDIC (Allied Submarine Devices Investigation Committee),
it operated on the principle of using a time measurement between the time of a
pulse transmission and the return of a reflected signal (echo) from a distant
object to determine the distance to that object. By making the transmitted
pulse directional, some measure of the direction to the distant object and,
thusly, its approximate location could be determined. If the pulse were
directed downward, a bottom echo could be used to determine the depth of water.
Gradually, over the years, the term ASDIC gave way to the more appropriate term
sonar, Sound Navigation And Ranging, a term that closely resembles radar, its
electromagnetic echo-ranging counterpart.

Since World War II, sonar systems, which had mostly been limited to military research and applications, have come into an ever-increasing use in civil fields. An important early application was the use of echo sounders by the fishing industry to locate schools of fish. However, it was not until the 1960's that underwater instrumentation really blossomed for commercial applications.

Early in the 1960's, Bendix developed the original acoustic transponder as part of an underwater navigation system called ARIS. In the years that have followed, several companies have developed systems, patterned after ARIS, primarily in response to the needs of offshore petroleum and mining industries.

Underwater navigation and positioning is only a small part of the underwater acoustic field. Many devices have been developed to communicate within or explore water bodies. One of these equipment in particular, the side scan-sonar, can provide a quite accurate interpretive image of bottom topography. It was with such a device that a team from the Coast Guard Research and Development Center located the remains of the ill-fated ore carrier EDMUND FITZGERALD in November of 1975, at the bottom of Lake Superior in 500 feet of water.

2.6.3 Water as a Signal Propagating Medium

From the point of view of sound transmission, the ocean (like other water bodies) is not the homogenous medium that it might appear to be. It contains foreign materials and has boundaries, regular and irregular, which restrict and otherwise influence the travel of sound in water. It contains varying amounts of salinity, has a non-uniform, non-linear temperature versus depth characteristic and exhibits a pressure that increases with depth. All of these factors cause sound energy to be spread, absorbed, ducted, reflected, refracted, and generally bent as it travels with varying velocity through the medium.

The ocean contains a large number of foreign materials. These include gas bubbles, bits of plant and animal life, and man-made objects, all of which cause scattering of sound energy. The scattered radiation is largely removed from the sound wave, although certain reflections might serve to reinforce the sound field in certain areas.

The ocean floor is a sound-reflecting surface. The characteristics of the reflections largely depend upon the frequency of the sound and the composition and terrain of the floor. Sand and rock reflect quite well, whereas mud is a poor reflector.

The surface is a near perfect reflector for underwater sound. A flat surface responds to sound as does a flat mirror to light. Generally, though, a flat surface does not exist and the surface is continually changing, presenting an uneven boundary. This results in a diffuse scatter of the sound energy. As with scatter from foreign materials, the sound field may be reinforced in certain areas.

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Signal loss occurs as a function of increasing distance, being an inverse square law function for spreading, and an exponential function for scattering and attenuation due to absorption. The attenuation coefficient depends upon water depth (pressure), salinity, temperature, and the signal frequency. These same factors have a strong influence on the velocity of propagation.

Of salinity, pressure and temperature, temperature is the most influential factor on the velocity of sound. There is considerable variation in the temperature of sea water and there is almost always a layer in which the temperature varies with increasing depth. The resultant temperature gradient may occur at or near the surface or it may lie beneath a constant temperature layer. Sometimes such a layer lies between isothermal (constant temperature) layers and has a rapid change in temperature over a small depth range. These are called thermoclines or thermal layers. Their presence can produce sharp bending of sound waves and can sometimes even serve as reflecting surfaces. Bending is the result of refraction as the waves transit layers in which the propagating velocites differ. As a sound wave travels through the water, it bends towards the path that permits lower velocity.

The effect of salinity on absorption and propagation velocity is not very large and there is very little variation in salinity in the open ocean. However, salinity varies greatly wherever a fresh water and ocean water interface exists. Fresh and salt water do not generally mix completely and salinity varies with both depth and horizontal distance. The major effect of varying salinity is to refract sound waves, a more dominant factor than any absolute change in propagating velocity.

Depth is an important factor in both absorption and propagating velocity because of the change in hydrostatic pressure. Absorption decreases and the velocity of propagation increases as depth increases. However, depth affects absorption very little down to approximately 1000 meters.

As stated earlier, propagation varies with the transmission frequency. In general, the lower the frequency, the lower the absorption and, consequently, the further the sound wave will propagate. At very low frequencies (below 5 kHz) ambient noise (sea-state induced, marine life, ships' noises, etc.) is quite predominant and creates a poor signal-to-noise atmosphere. At very high frequencies (above 500 kHz) absorption due to the water's viscosity becomes dominant, thus limiting useful operating range.

For all the problems connected with signal transmission under-water, sonic frequencies are far and away superior to any other frequencies. Water penetration at higher frequencies is not sufficient for communicating information within the medium.

2.6.4 Production and Detection of Underwater Sound

Acoustic instrumentation requires that some device be used to produce acoustic energy from some other form of energy, e.g., electrical or mechanical. Such a device is called a transducer. It has the capability to either convert other forms of energy to acoustic energy, convert acoustic

energy to electrical energy, or both. The former is called a sound projector, its opposite is called a hydrophone and the combination hydrophone and sound projector is sometimes called a reciprocal transducer or more generally, just a transducer.

Energy conversion is most commonly achieved by taking advantage of two well known electro-physical effects; piezoelectric and magnetostrictive. The piezoelectric effect is apparent in certain crystals. The crystals either contract or expand in the direction of an electric field produced by a voltage applied across them. Conversely, a difference of potential is developed across the faces of the crystals when they are subject to mechanical stress. Crystals can be cut to produce or be sensitive to a certain frequency and when properly coupled to water can produce the desired frequency in water or sense that particular frequency. Other materials such as nickel will expand or contract in the presence of a magnetic field; hence, they are called magnetostrictive. Conversely, they will produce a magnetic field when subject to mechanical stress.

Arrays of piezoelectric or magnetostrictive elements can be aligned to produce a desired effect. It is sometimes desirable to produce an omni-directional signal in the horizontal plane. At other times, a directional or vertical signal transmission format might be best suited for an application, and so forth. These and other combinations of directivity, polarization, and power are, in part, a function of orientation and quantity of the acoustic elements in an array.

2.6.5 Acoustic Navigation and Positioning Methods

Many electromagnetic systems used for surface and space navigation have counterparts in the underwater environment. For examples, radar becomes sonar, and doppler radar becomes doppler sonar. Radio altimeters can be compared to depth sounders and hyperbolic or circular mode positioning systems such as Cubic Corporation's Autotape and Motorola's Miniranger are duplicated with nets of underwater acoustic beacons.

All of the above noted acoustic systems could be used for positioning with varying degrees of confidence or difficulty. To position with either sonar or depth sounders, the surveyor must have a precise knowledge of underwater characteristics in the area that he is surveying, e.g., precise bottom topography, location of prominent objects. Doppler sonar used in conjunction with a gyrocompass and timing source can be used to provide survey information relative to a starting point. However, both speed information (hence, displacement) provided by the doppler sonar and direction provided by the gyrocompass contain significant errors which grow with time, much as errors in an inertial navigation system. Underwater acoustic beacon (transponder) networks offer the best possibility for precision acoustic surveying.

It is possible, using industry-available equipment, to deploy an acoustic beacon navigation and positioning system to provide coverage in an area exceeding 600 square miles, in deep, open water. Coverage would be very much less in restricted shallow waters and can only be determined on a by-case basis. Accuracies in the 2-3 meters range, using three or more lines of position (LOP's) for confidence, are being claimed (16,17,18).

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2.6.6 Acoustic Beacon Navigation and Positioning System
Operating Principles

Sonar, doppler sonar, and depth finders, although quite useful for general marine navigation, are not very useful for surveying. These systems will therefore not be discussed here. On the other hand, some acoustic beacon systems have been designed for precision marine surveying and are the major subject of this report.

Acoustic beacon navigation and positioning systems (ABNPS) operate on the multilateration principle. Several beacons are deployed near the ocean floor. The signals from these beacons are received aboard ship where the slant range to each beacon is determined from measurements of time and the average velocity of sound in water. A data processor then combines the information for all LOP's and computes a position relative to the beacon network.

There are two basic types of ABNPS. When the beacons are operated to provide a continuous tone, the system operates in a doppler mode. When the beacons are designed to respond to an interrogation, the system is said to be operating in the pulsed or transpond mode. Commercially available systems are generally of one or the other, although combined systems have been developed (16).

It is important to distinguish between doppler sonar and doppler ABNPS. Doppler sonar systems operate on reflected signals, e.g., from the bottom or a water layer. Doppler ABNPS operate on an active signal (as transmitted by a beacon). The doppler phenomenon results from the time rate of change in the effective path length between the beacons and a moving vessel (ship). Continuous, highly stable, discrete tones are transmitted by a network of these beacons. The tones are received via a hydrophone and the frequency offset (shift) of each tone is measured. The data processing unit reads the shifts at fractions of a second intervals and determines vessel position relative to a previous location. Accuracies of a few centimeters on a fix-to-fix basis are claimed to be obtainable (19), but over a period of time the errors grow in the same manner as noted for doppler sonar. For this reason, a doppler ABNPS requires periodic updating to remove errors. This can be accomplished with inputs from a pulsed ABNPS; hence, a combined system would be preferable over a stand-alone doppler system.

A pulsed ABNPS can be a stand-alone system offering a potential accuracy of better than three meters relative to the transponder network. In this type of system, bottom-moored acoustic beacons are interrogated sequentially with a coded signal at a certain frequency. Upon recognizing its own code, a beacon responds with a discrete tone. The round trip travel time for each paired signal is processed and a position estimate is then made. Typically, a fix is available every thirty seconds in deep water and more often in shallow water (update intervals are a function of system range). Each position estimate in a pulsed system is independent of previous position estimates.

2.6.7   Operating Procedure for an Acoustic Beacon Navigation and
        Positioning System

A typical ABNPS is composed of a data handling system, a
ranging receiver, an interrogation unit, a transducer, and a number of beacons.
All items except the beacons are carried aboard the vessel in a central location
with the exception of the transducer which may be either hull mounted or towed.

The data handling system is an integral part of the entire
system. It could consist of a mini-computer, a terminal, a tape loader and an
X-Y recorder. The operator can enter a specially designed navigation program
into the computer manually via the terminal or automatically with the tape
loader. Program variables and system commands are then entered by an operator
with the terminal. The plot of the vessel's position, relative to the beacon
net can be produced on the X-Y recorder.

The number of beacons vary with the application and/or capacity
of a specific system. Since, for navigation purposes, a point in space is
adequately defined by three coordinates, a beacon array usually consists of a
minimum of three beacons deployed in a triad configuration. If navigation is
required over an area larger than the coverage area of one triad, additional
beacons would need be deployed. A system that operates on four beacons simul-
taneously and has a maximum single array capacity of sixteen is commercially
available (18).

The critical part of an ABNPS operation is the initial deploy-
ment of the beacons. The most significant contribution to position errors in
this system is in the determination of depth and spacing of the underwater
beacons. If anomolous sound propagation conditions are anticipated, it may be
desirable to deploy only one beacon at first. Using this beacon, experiments
can be conducted to determine such things as maximum range and ray paths. This
aids in determination of proper spacing for optimum net coverage and accuracy.
In order to ensure maximum accuracy, the beacons are placed using good hydro-
graphic survey methods and procedures (visual, electromagnetic, etc.).

As discussed before, the sound wave is bent as it travels
through the water, therefore, the travel time to a beacon is not directly
proportional to the geometric slant range. A piecewise-linear approximation to
the vertical sound velocity profile must be made and entered into the system's
data processor. Since estimates of the profile have a large effect on accuracy,
it is important to estimate as accurately as possible. One method of accomplish-
ing this is to obtain an independent profile recorded by a bathythermograph. A
linear approximation, depth versus sound velocity (user-chosen increments), is
then developed. It should be noted that only the vertical velocity profile is
generally accounted for in ABNPS. The horizontal profile varies quite little
over a long distance in the open ocean, but can vary greatly in near-shore,
shallow-water applications; a definite system error potential.

The typical ABNPS beacon is surrounded by a flotation collar
and connected to an anchoring weight by a lightweight tether. NOTE: Both a
pulsed and a continuous beacon might be deployed on the same mooring. The
length of the tether is selected to suit the conditions in the deployment area

(water depth, desired range, boundary conditions, etc.) with the primary objective being to keep it as short as possible. The entire package can be placed into position in much the same way as a buoy, only the beacon is smaller and is sub-surface moored.

Once the beacons have been deployed, the array must be calibrated to obtain precise beacon coordinates. Three calibration methods are generally known to be useful; positions obtained from accurate surface navigation, from a cloverleaf and baseline crossings pattern or an iterative least squares fitting procedure. The first method demands extreme effort to obtain good accuracy. The second method involves considerable time and accurate maneuvering of the deploying vessel. Both of these methods yield a direct tie for the beacons to the surface navigation geographic reference although the surface navigation method will likely be the predominant factor which limits the ultimate accuracy of the ABNPS deployment. The third technique requires the least amount of time and does not involve any unusual vessel maneuvering. After calibration by this method, accurate navigation, relative to the array, is possible with a 2-3 meter uncertainty.

Array calibration by the iterative least squares fitting routine involves several measurements of the travel time of the responses from all the beacons taken at several points along a circular path around the array, plus one additional point within the array. The ABNPS data processor then performs the fitting routine on all of the data. The entire deployment and calibration procedure could be completed within one working day, given a reasonable degree of success, and providing an above surface geodetic reference has been established or is already available.

A calibration procedure which combines the first and third methods noted above has the potential of good navigational accuracy with respect to a selected geographical reference. It is well known that survey operations using the U.S. Navy navigation satellite system, TRANSIT, can yield absolute geographic positions within five meters accuracy if a sufficient number of satellite passes (about two weeks worth) are observed at a particular position. A vessel which has been outfitted with satellite, ABNPS and data processing equipments and rigidly moored within the operating area of the ABNPS array would have the capability of determining the geographic position of all the beacons within the array. This would be a time-consuming and costly effort, however, an ABNPS operating accuracy within ten meters would appear to be feasible.

Upon completion of calibration, navigation within the field of the array may commence. The beacons are interrogated by operator command or by pre-arranged computer control. The command is encoded in the proper format and transmitted by the vessel's transducer. The underwater beacons reply in a formatted sequence with a uniquely coded signal. The replies are picked up with the vessel's transducer and applied to the ranging receiver which has the capability of determining the slant range to several beacons (typically three or four). The slant ranges are then processed by the ABNPS data processer to determine the vessel's position which can then be displayed by various means. An X-Y recorder plot, as noted above, is a popular method for navigating.

Depending upon the desires of the ABNPS user, the beacons can be recovered or left in place when a mission has been accomplished. If left in place, the beacons could continue to provide navigation information for a period of days or years depending upon the type of beacon, the size of its power supply, and the number of replies that it was required to make. The vessel personnel would only have to make new sound velocity measurements in order to use the system at a later date since all of the other information would be known and remain unchanging under normal circumstances. Verification of beacon placement could be done with an abbreviated calibration procedure if there was reason to suspect that a beacon had somehow been moved from its initial position.

Properly outfitted beacons may be recovered after a particular mission is completed. The beacons would have to be fitted with a device that releases it from the tether upon recognition of a properly coded command developed in the encoder mentioned above. The released buoy would float to the surface where it could be recovered. After being recovered, many types of beacons can be refurbished, if necessary, and redeployed. Refurbishment might include electronic repairs, battery replacement and/or case renewal.

2.6.8 Accuracy Considerations

The capability of the user to determine accurate beacon locations will limit obtainable system accuracy, and even in the best of conditions, the nature of the medium will make this determination difficult, especially if it is desired to have reference to a known geographic datum. If a geographic tie is not desired/required, navigation in a relative mode can be accomplished fairly accurately, given a good calibration of the beacon array. Here again, though, a good initial estimate of the locations of the beacons is important. During system calibration, the calibration program iteratively makes "best guess estimates" of individual beacon locations. Obviously, an accurate initial position estimate will enhance the accuracy of follow-on estimates. In practical application this will reduce the necessary amount of calibration data, thereby reducing calibration time.

During calibration and subsequent navigation operations, three error categories occur in distance determination from time measurements. The first category is instrumental errors. Examples are timing base anomalies and transponder response or receiver recognition delays. The second category concerns erroneous estimates of the speed of sound in the medium. Up to a three percent variation of the nominal 1528 m/sec propagation velocity can occur, depending upon water temperature, depth and salinity. The third error category results from the sound ray being curvilinear. The straight line distance between the transponder and the beacon is less than the ray-path arc length, however, the time required to traverse the ray path is less. If the range is estimated to be the average sound velocity times the time measurement along the chord, it will turn out to be short of the true value.

Generally, when an interrogation signal is transmitted, it actuates several beacons in a sequential manner. If the vessel being navigated is moving during this operation, significant errors could develop in the position solution. This form of error can be compensated for by using a method called

the "running fix." Travel is sensed from a speed log input, for example, and is vectorially applied to the observed ranges to compensate for this effect. The accuracy of the travel sensor must be considered in the total error budget.

Very little information is available concerning the use of ABNPS in shallow water (less than a hundred meters) since these system are primarily designed for deep ocean applications (water depths up to several kilometers). As a result, shallow water accuracy information will not be presented here. In deep water, using a pulsed system, inaccuracies of two-three meters are being claimed for positioning relative to a beacon array (17,20) and three-four cm on a fix-to-fix basis when using a doppler system (16). NOTE: The doppler system must be updated periodically with actual position information. When a pulsed system is tied to a satellite navigation system, geographic coordinates of the beacons can be provided with an accuracy which is almost comparable to a multiple pass satellite fix (21).

2.6.9 Potential Application to Buoy Tending Operations

Acoustic beacon navigation and positioning systems have been primarily designed to fit needs of the offshore sub-surface industries of petroleum, mining, and research. And although some deep ocean buoys have been set with the aid of ABNPS to support commercial ventures, very little if any work has been accomplished in setting buoys (or other markers) in shallow water. There are at least two good reasons for the lack of work in this area; a need has not been exhibited and the range of ABNPS is severely limited in shallow restricted waterways.

Most Coast Guard buoys, particularly those requiring position accuracy of a few meters, are located in water depths less than 15-20 meters and in areas where navigation is restricted by bottom topography and manmade structures (piers, etc.). The R&D Center estimates that under these conditions, a theoretical maximum system range might be only 2-1/2 kilometers and that the underwater beacons would need spacing at about 300-meter intervals (22). Navigation within this small area could probably be accomplished with accuracies similar to those of deep water systems, but the merit of such an operation is dubious. It would be a costly operation which could most likely be done with a much less costly surface navigation method, particularly in areas where optical positioning methods are usable.

2.6.10 Safety Considerations

There are no particularly unusual safety precautions to be observed during deployment of an acoustic beacon navigation and positioning system. Placement of the beacons has been likened to buoy placement, an area in which the Coast Guard has considerable expertise. Handling and repair of the beacons might create a situation in which various types of batteries are encountered by maintenance personnel. Battery handling is another area in which Coast Guard personnel are trained. As concerns on-board equipment, ABNPS's operate in a manner similar to depth sounders and sonars which are widely in use aboard Coast Guard vessels.

2.6.11   Characteristics of an Example Acoustic Beacon Navigation
         and Positioning System

Perhaps the most commonly used commercial underwater navigation
and positioning systems are those manufactured by Ametek-Straza Marine Products,
AMF Sea-Link Systems, Honeywell Marine Systems or Ocean Research Equipment, Inc.
From this list, two systems have been selected for presentation here, based upon
availability of information and apparent possible suitability to buoy-tending
operations.   One system is the ATNAV II manufactured by AMF Sea-Link and the
other is TRANSNAV 6000 manufactured by Ocean Research Equipment.   The following
information is available in literature provided by the manufacturers:

The ATNAV II system determines the position of a surface
vessel and a tethered vehicle or submersible by measuring the slant range to
any four of as many as 16 beacons.   Range information is converted into X, Y and
Z (if required) coordinates relative to the beacon grid.   This operation is
automatic, requiring no hand plotting.   The shipboard equipment consists of a
Command/Interrogator, Ranging Receiver, Control Display Subsystem, and a trans-
ducer which may be towed or hull mounted.

With the TRANSNAV 6000, surface navigation is accomplished by
ranging to four seafloor mounted beacons.   To navigate a submersible or tethered
vehicle, one of the four beacons is directly mounted to the vehicle being navi-
gated, and control and tracking is exercised by the surface vessel.   Vessel
location is plotted relative to the beacon grid.   Shipboard equipment consists
of an Interrogator/Receiver, Processor/Plotter, and a hull-mounted or towed
transducer.

The cost of either system is somewhere between $100K and
$200K for equipment acquisition.   The total cost varies widely depending upon
selected options and, in the case of the ATNAV II, the number of beacons
purchased.   Beacons cost between $2K and $6K depending upon sophistication,
specified underwater lifetime, and environmental packaging.

Table 2-12 tabulates specifications of both the ATNAV II and
TRANSNAV 6000 systems.

2.6.12   Conclusions

The primary factor which should affect a user's decision in
selecting an acoustic beacon navigation and positioning system for precision
positioning is cost versus utility of application.   An ABNPS may cost as much
as $200K for equipment acquisition alone.   Maintenance costs are also high
because of the need to periodically service or replace the underwater beacons.
In this regard, low-cost, short-lifetime disposable beacons may be used and
discarded after each operation, or more expensive beacons with underwater life-
times of up to three-five years for each deployment may be used and serviced as
necessary.   The purchase price for disposables could be less than $1K.   The
purchase price of repairables could be as much as $6K or $7K and each scheduled
refurbishment might run about 30 to 50 percent of that (not including retrieval
and replacement operations costs).

The most useful applications for ABNPS are below the surface in deep water. Navigation of submersibles and location of underwater objects are examples. Underwater operations in shallow water and surface navigation are less useful. This is because of signal propagation anomalies caused by irregular and restrictive boundary conditions or range limitations as a function of the maximum non-reflected sound wave path (noting that the sound wave path is curved upward).

The position accuracy of ABNPS can be quite sufficient to position floating aids to navigation if placement and calibration of the underwater beacon net is accomplished in a precise manner. However, it is the nature of the placement and calibration method to require accurate surface position determination by another means; hence that means could probably be used to position the floating aids to navigation directly.

Because of the high cost as compared to usable coverage area and because some type(s) of surface position determinations would appear more useful in most applications, acoustic beacon navigation and positioning systems are not considered to be a good alternative for placement of Coast Guard floating aids to navigation.

2.7 Multi-Sensor Methods

2.7.1 Introduction

All of the positioning techniques discussed in the other sections of this report have application limitations for buoy placement operations. Some can provide no lines-of-position (LOP), like the precision gyrocompasses alone; others offer only two LOP's, such as inertial guidance and some radiodetermination systems. Optical and short-range radiodetermination require good visibility and/or unrestricted line-of-sight (LOS) between mobile and shore-based installations. The present Navy Navigation Satellite System provides only periodic navigation information. Underwater acoustic systems are extremely difficult to tie to the national triangulation network.

In order to resolve the above noted and other limitations, either one of two approaches must be pursued; a wide-area-coverage system that provides uniformly good accuracy must be developed, or a combination of techniques must be employed. One wide-area-coverage system to suit all applications is an obvious choice, but no such system exists. The developing Global Positioning System (GPS) has promise of fulfilling the desired criteria, but is not projected to be available until the late 1980's. In the meantime, a combination of existing techniques would suffice. This section examines integrated (multi-sensor) systems which have been developed by commercial companies to suit the needs of a wide variety of marine users. Comments are also made concerning some considerations for the development of a system(s) specifically for buoy-placement operations.

2.7.2 Description and Concepts

Multi-sensor, compound or integrated navigation systems, as they are variously called, employ more than one method of collecting data to establish navigation parameters. Perhaps the most simplistic form is the combination of a gyrocompass repeater with an optical sighting instrument such as an alidade or a pelorus. The opposite extreme is a system that is computer-controlled and provides hard and/or soft copy of navigation parameters which have been computed from the inputs obtained from a wide variety of sensors.

No matter what the combination of sensors and control, multi-sensor systems are used for any of three reasons: (1) sufficient LOP's are not available from a single sensor; (2) one or more sensors are needed to bound the errors and limitations of other sensors; and (3) increased fix confidence is desired. One can imagine many situations for which three high-confidence LOP's can not be obtained by a single method, such as the lack of landmarks to sight on with optical devices. An example of sensor bounding is the combination of an inertial guidance system and a doppler sonar. The doppler sonar provides a reference velocity to damp the residual velocity errors of the inertial system. Fix confidence can be greatly enhanced by the use of multiple LOP's, especially if those LOP's are compatible, i.e., application errors of all LOP's are similar in nature and magnitude. An example is the reduced size of an error ellipse when using four instead of three LOP's. For two LOP positions, uncertainty is described by t^2 (bi-variant) confidence level factors of ∞ for any confidence level. For three or more LOP's, the uncertainty is described by families of error ellipses for different confidence levels.

The design structure of any multi-sensor system should conform to a few simple rules: (1) it should be subdivided into three distinct groups, a sensor group, a central measurement processor group, and an information display and collection group; (2) individual sensors should be grouped in subsections according to compatibility, particularly as regards time stability; (3) the navigation processor should employ a data sorting and weighting capability, e.g., a Kalman filter; (4) standardized equipment interfaces should be used wherever possible; and (5) both hardware and software should be modularized. A central processor is a necessary requirement for most multi-sensor systems because it provides the capability to analyze situations at a rate that can not possibly be matched or even approximated by manual means. This is an important consideration when a vessel is involved in close maneuvers. An adaptive filter of the Kalman type has advantages in flexibility over filtering algorithms which require a complete a priori knowledge of component characteristics or system configuration. The use of some sort of filtering method, however, is near-essential to properly determine the value of measurement data which have been collected from a variety of sensors which could collectively exhibit widely varying degrees of confidence.

2.7.3 Common Systems

All commercially available integrated marine navigation systems are built around a TRANSIT satellite system receiver for one simple reason. TRANSIT offers world-wide navigation with uniform accuracy. However, navigation information is only provided on a periodic basis. Other navigation sensors must be used to provide information that will allow a navigator to "dead-reckon" until a subsequent satellite fix can be achieved. The sensors most commonly employed for this purpose are a gyrocompass and some form of speed log (in the interest of economy, installed capabilities are often used).

2.7.4 Elaborate Systems

A system designer, contemplating all the means available to improve on a system's fixing capability, can easily develop an ulcer trying to select the best combination. Here are some of the methods that could be considered:

Satellites - As stated above, this equipment is common to all commercial integrated navigation systems, though not absolutely necessary.

Long-Range Radiodetermination - Systems such as Loran-C, Decca Main Chain and Omega fall into this category. For general navigation purposes, one or more of these systems in combination can be used as the primary sensor. For survey work, however, precision is inadequate with today's receivers.

Short-Range Radiodetermination - Several manufacturers market short-range radio systems that are advertised to provide a high degree of accuracy within a limited service area. Some of these suffer from a possible lane count loss, in which case the less accurate long-range radio system can be useful to re-establish lane count, depending upon its magnitude of fix uncertainty versus the lane width of the short-range system.

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Underwater Acoustics Beacons - Excellent relative navigation can be accomplished within a very small service area. Less accurate absolute navigation can be accomplished with some difficulty.

Vessel's Speed Log - This could be a shaft RPM counter, pit log, or a doppler sonar. Both the RPM counter and the pit log are unable to sense vessel motion caused by water currents. A doppler sonar set in bottom-track mode is capable of providing true over-the-bottom velocity.

Inclinometer - Used to sense motion of the vessel about its pitch and roll axes. Data used to adjust data provided by range measurement sensors.

Gyrocompass - A practical necessity for multi-sensor systems.

Gravity Gradiometer - The altitude channel of satellite navigation systems are inherently unstable. This device senses the variation in the earth's gravitational field. Gravitational variations can also be approximated by computer software.

Water Depthfinders - Many marine activities require a precise or, at the very least, a good knowledge of the water depth. Often times this information can be used for vessel maneuvering over a prominent bottom feature.

Inertial Guidance - Not a cost-practical method for most commercial work, but employed by the U.S. Navy on some of its vessels.

Laser and Other Optical Methods - Can be used for high accuracy when the vessel is performing a low dynamic operation. Passage through a narrow waterway, docking and anchoring maneuvers are examples.

Fortunately for the design engineer (and his ulcer), practicality should prevail and his selection list can be considerably shortened by specific application requirements. For example, if the system is to be designed primarily for general navigation, some of the refining methods such as inclinometers and gravity gradiometers are of no consideration to him. On the other hand, these instruments would be useful to close navigation and survey work, whereas the long-range systems such as Loran-C, Omega, and Decca Main Chain would not be as important.

Once the selection of sensors has been made, the next consideration is how to handle the data. It is quite possible that a system involving only two or three sensors could be operated by semi-manual means, i.e., each device develops and displays its navigation information and the navigator manually combines all information in order to produce a most probable position (MPP) and associated error ellipse to a described confidence level. As the number of sensors are increased, this method becomes impractical for two reasons; it is slow and is highly prone to mistakes, sometimes referred to as operator error. The only practical solution is to have computations done automatically by an information processor. The processor accepts all data, sorts it according to various weighting factors, combines it with any software fitting routines and makes a determination of MPP and associated error ellipse. The three most

often determined parameters for navigation are vessel speed, heading and location. This information is then made available for display and logging, if desired. Logging of all collected data can be very useful in post-mission analysis. Certain techniques can actually improve upon the accuracy of the instantaneous on-site computations.

2.7.5 Accuracy Considerations

It is difficult to put a single number on or make a functional expression of the accuracy of a multi-sensor system. Accuracy is a function of system components, local operating conditions, adequacy of calibration and the manner in which the system is operated. However, it is safe to say that the overall accuracy will be somewhat reduced from that of the single most accurate sensor, since the basic concept of system operation dictates that computed solutions will lie somewhere amidst the individual sensor solutions. A good software system will properly weigh individual bits of data so that the final solution is near that of the best sensor.

To put the system accuracy of commercially available systems in perspective, error estimates for the satellite-based Magnavox Model 200 Integrated Navigation Systems, as contained in reference (22), are related as follows: The non-linear growth of system errors is plotted as a function of time (0-2 hours) since the last satellite fix update versus the operating conditions and complexity of the expandable system. The accuracy of an austere system under poor conditions varies from 80-260 meters. For good conditions the range is from 70-145 meters. For a complete system under poor conditions the range varies from 70-175 meters, and from 60-110 meters under good conditions. It should be noted that the accuracy of a single-pass satellite solution can, only under ideal circumstances be better than 50 meters.

2.7.6 Potential Application to Buoy Tending Operations

A form of multi-sensor systems is presently being used by buoy tender personnel throughout the Coast Guard. It uses an information processor, a group of sensors and a data-collecting and display element; all the basic ingredients of a multi-sensor system. The information processor is the conning officer who sorts the information being provided him by his bridge personnel and makes a best-guess estimate of the proper moment to drop a buoy anchor. The sensors can be any of a wide variety of types, including a radar, a depth sounder, a Loran-A or Loran-C set, a gyrocompass, various optical methods, and the natural terrestrial ranges observed by the conning officer. Data collection is done manually and the positioning computations are done on a chart or plotting board. So, obviously, multi-sensor systems have a place in Coast Guard buoy-tending operations.

Unfortunately, present operating procedures violate several of the basic concepts of the design and use of multi-sensor systems. For one thing, practically all phases of buoy placement involve the manual operations of several personnel whose collective outputs are sorted for decision-making by one or two humans. There is no doubt that this method is riddled with possibilities of operator mistakes. Automatic data processing is known to be more advantageous. Another cardinal rule to be observed when using multi-sensor

systems is that all range measurements should be time correlated. As an example, the gyrocompass heading, the water depth, a horizontal sextant reading and an LOP or two from a radio system measurement has to be made practically simultaneously in order to minimize errors due to the motion of the vehicle while the measurements are being made. This is difficult to accomplish by manual means. Automatic systems can do this in a split second. For the above example, all other readings would be recorded at the moment the sinker is tripped.

2.7.7 Conclusions

Multi-sensor procedures are presently being used within the Coast Guard to provide position information for buoy-placement operations. However, these systems are not being employed in a manner which ensures optimum repeatable accuracy with minimum effort. There are many commercial systems available which satisfy minimum effort and repeatable operations, but none are known to provide the overall system accuracy needed for buoy tending, nor do they incorporate the Coast Guard's most used positioning sensor, the sextant.

A need exists to update the capability of utilizing presently installed navigation sensors. Additionally, it is apparent that some of the sensors discussed in the other sections of this report could be useful for incorporation with a buoy tender multi-sensor system. The exact nature of how this can be accomplished can only be determined on a district-by-district, area-by-area and even a unit-by-unit analysis of what is required to suit all of the widely varied buoy-placement conditions. Initial efforts in this regard could be the development of an interface(s) to tie presently available sensors with an automatic (computer-aided) data analyzing and display subsystem, establishment of frequent and stringent calibration requirements and the proper training of personnel in the use of automated systems. These efforts could very well result in a most cost-effective solution for reducing the possibility of misplaced buoys.

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TABLE 2-12

ACOUSTIC BEACON NAVIGATION SYSTEMS CHARACTERISTICS

CHARACTERISTIC	AMF SEA-LINK ATNAV II	O.R.E. TRANSNAV 6000
Accuracy:	2-3 meters[a]	3 meters[a]
Resolution:	1 meter	0.5 meters
Range (slant):	15 kilometers[b]	15 kilometers[b]
Water Depth:	To 6000 meters	To 2000 meters
Number of Transponders:	Up to 16	Up to 4
Maximum net coverage area:	1000 square kilometers	100 square kilometers
Number of LOP's processed: simultaneously	Up to 4	Up to 4
Operating Frequencies:	Interrogate: 9 & 11 kHz Reply: 7.5 - 15 kHz	7.5 kHz 10 - 13 kHz
Maximum # of command codes:	70	512 minimum
Transponder battery life:	Up to 2.5 years	Up to 2.5 years (5 years opt)
Features:	Surface Navigation Submersible Navigation Geodetic software Automatic control Self-Calibrating Variable plot size Post plot capability Auto. data smoothing Magnetic cassette program input and data storage	Surface Navigation Submersible Navigation Geodetic software Automatic control Self-Calibrating Single plot size Post plot capability (opt) Auto. data smoothing Magnetic cassette program input and data storage (opt) Manual and hard copy (std)
System components:	Encoder/Amplifier Ranging Receiver (16 ch.) Naivgation Processor Dual Magnetic Cassette Transducer Silent Terminal/Printer Plotter Transponders	Interrogator/Receiver Transducer Processor/Plotter X-Y Recorder Command Unit (opt) Silent Terminal/Printer (opt) Line Tape II (opt) Transponders
Transducer options:	Hull mounted or towed	Hull mounted or towed
Volume of shipboard equipment less transducer:	0.44 cubic meters	0.5 cubic meters (approx., incl. option equip)
Maximum power required (shipboard equip):	115 or 230 VAC, 50-400 Hz, 1000 W (approx)[c]	115 or 230 VAC, 47-63 Hz, 1000-1500 W (approx)[d,e]
Cost:	$100K to $200K (approx)	$100K to $125K (approx)

[a] Under ideal conditions

[b] Depending upon water depth and conditions

[c] Underwater beacons are battery operated

[d] Depending upon options

[e] Underwater beacons are battery operated. Some shipboard equipment may be battery operated (optional).

3.0 OVERALL CONCLUSIONS

No single method can be used to satisfy the widely-varied buoy placement scenarios. Instead, a combination of methods (including those presently used) would be most appropriate. Furthermore, no single combined-methods system would fit all applications unless it consisted of an all-encompassing set of equipments and procedures; an impractical solution.

Laser rangefinder, precision gyrocompass, radiodetermination, and satellite methods are considered to have applicability to buoy placement operations, either as stand-alone or for incorporation with a multi-sensor system. Inertial guidance and underwater acoustic methods are not considered to have practical application.

Laser rangefinders offer the highest degree of obtainable accuracy for all the methods studied. They can be either portable or permanently installed (ship and shore) but exhibit poor dynamic performance unless an expensive automatic tracking capability is provided.

Precision gyrocompasses could be an asset for improved buoy placement capabilities. Alidades, peloruses, radars, lasers, and other devices can or do use reference bearing information provided by a gyrocompass. The gyrocompasses which are presently installed on most Coast Guard buoy tenders do not provide a sufficiently accurate reference, especially when any of the above normal systems are used to sight on distant targets.

There are several radiodetermination systems which have either demonstrated or claim to have sufficient accuracy to be useful in buoy placement. Most of these systems can be portable, requiring an on-shore contingent to deploy base stations in cooperation with the requirements of the actual buoy placement personnel, or on the other hand, the base stations might be permanently installed. Regarding the latter deployment, related R&D Center work has shown that, in order to provide reasonable system accuracy and coverage, several more than the normal 2-4 base stations must be installed in even the most hospitable operating areas.

The present navigation satellite system, which is operated by the U.S. Navy, does not provide an accurate dynamic operating capability, but does provide an excellent surveying capability that can be quite useful in establishing survey control. This type of surveying can be cost competitive with conventional methods under certain circumstances.

A developing satellite navigation system, NAVSTAR GPS, which will be operated by the U.S. Air Force, is projected to provide world-wide, continuous, high dynamic position location capability by the late 1980's. When fully implemented, this system has promise of becoming the navigation system most commonly adopted by U.S. Government agencies requiring navigational capability. It must be noted, however, that buoy positioning does not require high dynamics and that relatively gross navigation capabilities are inadequate to achieve survey-level results.

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Inertial guidance offers a fully self-contained navigation system, a highly desirable capability. However, the present-day accuracies as well as those projected to be obtained within the next decade are not sufficient for use in buoy placement.

Underwater acoustic systems are not considered useable from a practical standpoint rather than from an accuracy standpoint. These systems can provide very good accuracy in small coverage areas, but the cost is great, not only for system acquisition, but also for maintenance. Additionally, wherever this type of system can be used for buoy placement, an equally useable, less costly and more practical surface method could be employed.

A concern of the Coast Guard Aids to Navigation program manager is that systems might not be very useful if there exists an inherently high operator-error potential. All of the methods investigated in this report contain systems that are automatically controlled and essentially operator-independent. Advances in microprocessor and minicomputer control have made this method a most practical alternative to other methods which are error-prone and often laborious.

Many more conclusions can be drawn concerning the advantages and disadvantages of individual methods and systems. Some of these are presented in the conclusions section for each method, others are left to the readers. Tables 3-1 and 3-2 contain summary information to assist in the development of those conclusions.

TABLE 3-1

COMPARISON MATRIX FOR METHOD CHARACTERISTICS

METHOD	NUMBER OF LOP'S	RANGE OF SINGLE LOP	COVERAGE AREA	ATTAINABLE ACCURACY (a)	USER EQUIPMENT ACQUISITION COST
Inertial Guidance					
Aided:	2	N/A	Unlimited	30 m/hr	$140K - 1M
Unaided:	2	N/A	Unlimited	30 m/hr	$140K - 1M
Laser Rangefinder					
Continuous Wave (CW):	(b)	Line of Sight (LOS)	Visible	1 m or less	$5K - 25K
Pulsed:	(b)	LOS	Visible	5-10 m	$15K - 100K
Precision Gyrocompass:	1	N/A	Unlimited	0.0004 degrees	$100K - 200K
Radiodetermination					
Short Range:	1-3	LOS (15 km to 250 km)	25 km^2 to 25K km^2 (c)	1.5 - 15 m (d)	$10K - 150K
Medium Range:	1-3	250-750 km	25K km^2 to 70K km^2 (c)	10 - 100 m (d)	$50K - 200K
Satellite					
TRANSIT Navigation:	(e)	N/A	World-Wide	100 - 300 m	$15K - 50K
TRANSIT Survey:	(f)	N/A	World-Wide	1 - 5 m	$50K - 150K
Global Positioning System (GPS) Navigation:	(g)	N/A	World-Wide	8 m (h)	$10 - 35K (h)
Underwater Acoustics					
Pulsed:	1-4	8 km (i)	1K km^2 (i)	2 - 3 m	$100 - 200K
Doppler:	(e)	8 km (i)	1K km^2 (i)	1 m or less	$25K -

(a) As commercially advertised. Confidence interval varies, see individual descriptions.
(b) Can provide range to several stations, one at a time.
(c) R&DC estimate for no ambiguity, unrestricted LOS (short-range systems), optimum deployment geometry of 30° to 150° crossing angles coverage.
(d) Accuracy varies with range from transmitting stations.
(e) Several range measurements versus time of signals from a single transmitter.
(f) Several range measurements versus time of signals from several transmitters.
(g) Three or four channels of several range measurements versus time of signals from three to four xmtrs.
(h) Projected for late 1980's.
(i) Assumes deep, unrestricted water body. See report for restricted values.

TABLE 3-2

COMPARISON MATRIX FOR METHOD USEABILITY

METHOD	ON-BOARD EQUIPMENT PHYSICAL CHARACTERISTICS	DYNAMIC OPERATIONS SUITABILITY	SPECIAL SAFETY REQUIREMENTS	SPECIAL TRAINING (a)		PRACTICALITY FOR BUOY TENDING
				OPERATION	MAINTENANCE	
Inertial Guidance:	2 groups, medium bulk	Good	No	No	Yes	None
Laser Rangefinder:	Portable or installed system which requires small space on mast and medium inboard space	Not good for portable units, excellent for installed system	Yes	No	Yes	Fair
Precision Gyrocompass:	Would replace existing gyro-compasses with smaller space required	Good	No	No	Yes	Excellent
Radiodetermination:	Small bulk, small antenna to be mast mounted, could be portable	Good	No	No	(b)	Good
Satellite – Present:	Portable	Poor	No	No	Yes	None
Future:	Small equipment, small antenna to be mast mounted	Excellent	No	No	Yes	Excellent
Underwater Acoustics:	Requires a towed or hull mounted transducer, small bulk equipment	Fair	No	Yes	Yes	None

(a) Instruction requirement of less than two weeks not considered special; two weeks or longer is considered special requirement.
(b) Training requirement varies with system chosen; some are relatively common usage equipment, while others have high degrees of complexity.

NOTE: Special training, as used here, only applies to operation and maintenance of the particular systems after they have been installed by competent personnel, thoroughly trained in the installation procedures for that particular system. It will be necessary for the Coast Guard to initiate installation-type training courses for lasers, radiodetermination and underwater acoustics methods. Inertial guidance and precision gyrocompasses should be constractor installed. Present satellite methods and well as future methods would also require contractor installation for fixed shipboard installations, however, portable installation for the present system does not require special training (more than two weeks).

GLOSSARY

absorption - The taking up of energy from radiation by the medium through which the radiation is passing (23).

accelerometer - An instrument which senses or measures the change of motion or velocity of a vehicle (1).

accumulator - A specific register, in the arithmetic section of a computer, in which the result of an arithmetical or logical operation is formed; here numbers are added or subtracted, and certain other operations such as sensing, shifting, and complementing are performed (23).

acoustic navigation - Navigation by means of sound waves whether or not they are in the audible sound range. Also known as sonic navigation and sonar navigation (23).

alignment (in inertial navigation equipment) - The orientation of the measuring axes of the inertial components with respect to the coordinate system in which the equipment is used (24).

attenuator - An adjustable or fixed transducer for reducing the amplitude of a wave without introducing appreciable distortion (23).

altitude - The vertical angle between the plane of the horizon and a line to an object, which is either defined or observed.

audit (as used herein) - An examination to verify positions of aids to navigation by highly skilled people using very accurate equipment.

avalanche - The cumulative process in which an electronic or other charged particle accelerated by a strong force collides with and ionizes gas molecules, thereby releasing new electrons which in turn have more collisions, so that the discharge is thus self-maintained (23).

azimuth - The horizontal direction of a celestial point from a terrestrial point, expressed as the angular distance from a reference direction.

ballistic damping error - A transient oscillatory error of a gyrocompass introduced during changes of course or speed as a result of the means used to damp the oscillations of the gyro spin axis. Also called damping error (30).

bathythermograph - A device for obtaining a record of temperature versus depth (pressure) in the ocean from an underway ship (23).

celestial sphere - An imaginary sphere of indefinitely large radius, which is described about an assumed center, and upon which positions of celestial bodies are projected along radii passing through the bodies (23).

centripetal force - The radial force required to keep an object moving in a
    circular path, which can be shown to be directed at the center of the
    circle (23).

choroid - The highly vascular layer of the certabrate eye, lying between the
    sclera and retina (23).

circular ranging - Determination of distance by various means such that the
    resultant lies somewhere on a circle of constant range from a transmitter,
    reflector, or fixed point.

clocked - Timed; as by time intervals generated by an electronic counter which
    counts phase reversals of an oscillator signal.

coherence - The existence of a correlation between the phases of two or more
    waves.

cooperative target - An object/device which readily reflects incident energy at
    the wavelength of concern, e.g., a prism is a cooperative target for light
    wave energy.

coordinate system - A system whereby linear or angular quantities, or both,
    designate the position of a point in relation to a given reference frame
    (28).

coordinate transformation - A mathematical or graphic process used to obtain a
    modified set of coordinates by rotating the coordinate axes from their
    point of origin (23).

coriolis force - A deflecting force exerted by the rotation of the earth upon
    any object in motion, diverting the object to the right of velocity in the
    northern hemisphere and to the left in the southern (1).

damping - The dissipation of energy in motion, especially oscillatory motion
    and the consequent reducion or decay of the motion (23).

dead reckoning - A method of navigation in which navigation between position
    fixes is accomplished in a relative manner with respect to the previous
    fix.

degree-of-freedom - Of a gyro, the number of orthogonal axes about which the
    spin axis is free to rotate, the spin axis freedom not being counted.
    This is not an universal convention. For example, the free gyro is fre-
    quently referred to as a three-degree-of-freedom gyro, the spin axis being
    counted (30).

demodulator - Device which recovers intelligence from a carrier signal which
    has the intelligence impressed upon it. Also known as decoder; detector
    (23).

diurnal - Pertaining to events which are completed within 24 hours and which
    recur every 24 hours.

divergence - Spreading with distance. Beam divergence is described by the angle formed by the beam axis and its radius.

Doppler effect - The change in the observed frequency of a wave due to the relative motion of the source or detector (23).

dynamic memory - Computer memory that is not of a permanent nature and requires periodic renewal.

earth rate - The velocity at which the earth rotates about its own polar axis. It is equal to 15.041088 degrees per hour and can be resolved into vertical and horizontal components.

EDM - Electronic Distance Measurement, or a device which does so.

ephemeris - A statement presenting positions and related data for a celestial body for given epochs (dates) at uniform intervals of time (28).

excited atom - An atom which has been raised to a higher than normal state of energy.

fathometer - Registered trade name for a sonic depth recorder.

fluorescence - Emission of electromagnetic radiation caused by, and only during, the flow of some form of radiant energy into the emitting body.

GaAs - Gallium-Arsenide; the most extensively studied material for semi-conductor lasers.

GDOP - A measure of the sensitivity of fix accuracy to errors in time difference measurements. It is a function of the LOP crossing angles and gradients (gradient being the rate of change of time difference per unit of distance).

geoid - The figure of the earth considered as a mean sea-level surface extended continuously through the continents (28).

geoidal height - Difference between reference spheroid and the geoid.

GHz - Gigahertz; 10^9 cycles per second.

gimbal - A device with two mutually perpendicular and intersecting axes of rotation, thus giving free angular movement in two directions. In a gyro, a support which provides the spin axis with a degree of freedom (23).

grid - A network composed of two sets of uniformly spaced straight lines intersecting in right angles.

gyro biasing - A method of minimizing undesirable gyro precessions by applying counter torques to the gyro.

gyro drift - Undesired precession of a gyro caused by such things as mechanical friction acting upon the rotor.

gyro(scope) - A mass rotating about an axis at high angular velocity and having a high moment of inertia (1).

gyro torquer - A gyro control which allows application of counter torques to provide desired stabilization of the gyro.

HeNe - Helium-Neon; typically used in neutral atom-type gas lasers.

heterodyne - To mix two alternating current signals of different frequencies in a nonlinear device for the purpose of producing two new frequencies, the sum of and difference between the original two frequencies (23).

hydrophone - A device that receives underwater sound waves and converts them to electrical waves (23).

hydrostatic (as used herein) - Pertaining to static pressure exerted by fluids.

hyperbolic LOP - A line of position in the shape of a hyperbola, determined by measuring the difference in distance to two fixed points (30).

hyperbolic navigation - Navigation by use of hyperbolic lines of position (30).

impurity - A substance that, when diffused into semiconductor metal in small amounts, either provides free electrons to the metal or accepts electrons from it (23).

inertia - That property of matter which manifests itself as a resistance to change in momentum of a body (23).

inertial navigation - Dead reckoning accomplished automatically by means of self-contained controlling devices that respond to inertial forces.

inertial space - A coordinate system or frame of reference defined with respect to the stars whose apparent position relative to the surrounding stars appears to be fixed or unvarying for long periods of time (23).

infrared radiation - Electromagnetic radiation whose wavelengths lie in the range from 0.75 um to 10 um.

injection station - In satellite navigation, an earth station which transmits data to satellites for the purpose of updating the satellites' navigation messages and other functions.

integrator - A device which approximates the mathematical process of integration.

interrogation (as used herein) - The process of transmitting a signal which is designed to trigger response from another device. A beacon might be interrogated by a signal transmitted by a transducer.

ionosphere - That part of the earth's upper atmosphere which is sufficiently ionized by solar ultraviolet radiation so that the concentration of free electrons affects the propagation of radio waves; approximately 70-80 km to indefinite height above the earth's surface (23).

irradiate - To expose to or treat by exposure to some form of radiant energy (26).

isothermal - Having constant temperature.

kHz - Kilohertz; one thousand cycles per second.

lapse rate - The rate of decrease of temperature in the atmosphere with increasing height. Sometimes used to describe other functions such as refraction index or any meterological element.

LASER - Light Amplification by Stimulated Emission of Radiation.

LED - Light Emitting Diode; a semiconductor diode, generally made from gallium-arsenide, that can serve as a light source when voltage is applied continually or in pulses (26).

LF - Low frequency; 30 to 300 kilohertz.

limiter - An electronic circuit used to prevent the amplitude of an electronic waveform from exceeding a specified level while preserving the shape of the waveform at amplitudes less than the specified level (23).

luminescence - Light emission that cannot be attributed merely to the temperature of the emitting body, but results from such causes as chemical reactions at ordinary temperatures, electron bombardment, electromagnetic radiation, and electric fields (23).

magnetostriction - Dependence of the dimensions of a ferromagnetic sample on the extent and direction of its magnetization (23).

MASER - Microwave Amplification by Stimulated Emission of Radiation

meridian - A north-south line from which longitudes (or departures) and azimuths are reckoned; or a plane, normal to the geoid or spheroid, defining such a line (28).

metastable state - An excited stationary energy state whose lifetime is unusually long (23).

MHz - Megahertz; one million cycles per second.

microprocessor - A single high-density integrated circuit which performs the functions of a central processing unit (27).

modulate - To vary the amplitude, frequency, or phase of a wave, or vary the velocity of the electrons in an electron beam in some characteristic manner.

m.s.e. - Mean Square Error; sum of the squares of the errors divided by the number of errors.

multilateration - Determination of position by the use of more than two lines-
of-position, all of which are measured distances.

Nd:YAG - Neodimium-Yttrium Aluminium Garnet; lasing material typical of high-
power optical rangefinders.

orthogonal - Right angular.

OSHA - Occupational Safety and Health Administration.

pendulum - A body, separated from a fixed point, which will swing freely under
the combined action of gravity and momentum (1).

phase - The amount by which a cycle has progressed from a specified origin.
For most purposes it is stated in circular measure, a complete cycle being
considered 360° (3).

phase-lock - Technique of making the phase of an oscillator signal follow
exactly the phase of a reference signal by comparing the phases between
the two signals and using the resultant difference signal to adjust the
frequency of the oscillator (23).

photon - A massless particle, the quantum of the electromagnetic wave carrying
energy, momentum, and angular momentum (23).

piezoelectric effect - The effect of some materials to become polarized when
mechanically strained.

pitch - An angle measured about an athwartship horizontal axis determined by
the intersection of the horizontal plane with the athwartship plane perpen-
dicular to the deck; the angle between the vertical plane through this
axis and the plane perpendicular to the deck through this axis.

platform - A base, used as a reference, from which measurements are made and/or
about which motions are sensed (1).

Pockels cell - A device containing an electro-optic crystal, using the Pockels
effect (a voltage applied across the crystal causes plane polarized light
propagating through the crystal to be resolved into two orthogonal vectors).
A crossed polarizer analyzes the output beam resulting in intensity modula-
tion.

point positioning - A method of surveying in which the surveyor establishes a
position by collecting all data while at a single point.

polarization - The process of producing a relative displacement of positive and
negative bound charges in a body by applying an electric field (23).

PPM - Parts Per Million.

precession - The angular velocity of the axis of spin or a spinning rigid body,
which arises as a result of external torques acting on the body (23).

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precision - A measure of the reproducibility of measurements, i.e., given a fixed value of a variable, precision is the measure of the degree to which successive measurements differ from one another.

profiling (in underwater acoustics) - The process of obtaining graphic representation of the variation of water depth, yielding a bottom contour.

quantum - The smallest amount into which the energy of a wave can be divided (27).

quantum mechanics - The science of all complex elements of atomic and molecular spectra, and the interaction of radiation and matter (27).

radial (as used herein) - One of a number of lines of position defined by an azimuthal navigation facility; identified by its bearing from the facility (24).

radiant energy - Energy passed on as electromagnetic radiation, e.g., radio, heat, or light waves (27).

radio sextant - An antenna with a high-resolution beam pattern that measures the angle between local direction references and an astronomical radio signal source such as an artificial satellite, the sun, the moon, or a radio star (23).

integral gyroscope - A single-degree-of-freedom gyroscope having primarily viscous restraint of its spin axis about its output axis; an output signal is produced by gimbal angular displacement, relative to the base, which is proportional to the integral of the angular rate of the base about the input axis (23).

reference table - A system of coordinates against which to gauge movement about a point.

refraction - The bending of oblique incident rays as they pass from a medium of one refractive index to a medium of another (27).

refractive index - The ratio of the velocity of propagation in a vacuum to the velocity of propagation in another medium.

refresh - In data processing, certain types of computer memory degrade with time or is used when recalled, and must be periodically rewritten. A refresh period involves reading the memory before it degrades and rewriting it again or completely replacing the information on a periodic basis.

resolution - The smallest change between two measurements which an instrument can indicate, e.g., the least significant figure in an instrument display.

retroreflector - Device which returns radiation along the same path as that from which it came, this property being maintained over a wide range of directions of incident radiation.

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rigidity - The quality or state of resisting a change in momentum of a body (23).

r.m.s. - Root-Mean-Square.

roll - An angle measured about a fore and aft axis in the deck; the angle is measured vertically in the athwartship plane, between its intersection with the horizontal plane and its intersection with the deck plane.

RSS - Root Sum Square; the square root of the sum of the squares. Commonly used to express total error.

rubidium standard - An oscillator/clock based upon the emission wavelength of rubidium and having an accuracy of approximately 10^{-12}.

scaling - Method of counting pulses with a scaler. Used when pulses occur too fast for direct counting by conventional means (a scaler produces a prescribed input pulse to output pulse ratio).

scattering - The production of waves of changed direction, frequency, or polarization when radio waves encounter matter (25).

Schuler period - 84.4 minutes; the undamped oscillatory period of a hypothetical simple pendulum whose length is the earth's radius.

sensor - The generic name for a device that senses either the absolute value or a change in a physical quantity such as temperature, pressure, intensity of light, sound or radio waves, and converts the change into a useful input for an information-gathering system (23).

shells - A set of orbital electron states that have the same principle quantum number and, therefore, have approximately the same energy level and average distance from the nucleus (23).

slant range (distance) - The distance between two points that are not on the same elevation (25).

SONAR - Apparatus or techniques whereby acoustic energy is used for SOund Navigation And Ranging.

spectrum - A display or plot in intensity of radiation as a function of mass, momentum, wavelength, frequency, or some related quantity (26).

spheroid - An ellipsoid; a figure resembling a sphere (30).

stable element - Any instrument or device, such as a gyroscope, used to stabilize a piece of equipment mounted upon an aircraft or ship (23).

stabilized gyroscope - A gyro which is used to establish a fixed reference from which movement or displacement can be measured. They may be used to establish horizontal and vertical references and may be used in groups of two or more to establish geometric plane of reference.

stabilizing platform - A platform mount used to hold sensitive optical instruments immobile. Gyroscopically stabilized mounts or platforms are common (26).

stable - Not subject to any change without the application of an external force.

star tracker - An automatic sextant which has the ability to sight on and continuously track selected stars throughout the day and night, providing continuous heading and position data (23).

step repeater - Repeater compass system using DC step-by-step motors to transmit information.

stratosphere - The atmospheric shell above the troposphere and below the mesosphere; it extends from the tropopause to about 55 kilometers, where the temperature begins again to increase with altitude (23).

synchro - Any one of several synchronous electro-mechanical devices used for transmitting and receiving angular position or angular motion over wires (1).

telemetry - Measurement with the aid of intermediate means which allows the data to be interpreted at some distance from the source (25).

theodolite - A precision surveying instrument consisting of an alidade with telescope, mounted on an accurately graduated circle, equipped with necessary levels and reading devices (28).

thermocline - A layer of water in which the temperature decrease with depth is greater than that of the underlying and overlying layers.

transducer - A device that transfers energy from one media to another.

translatory movement - Movement wherein parallel features maintain their orientation.

translocation (in satellite surveying) - A method which employs receiving equipment, located at separate points, collecting simultaneous data for the purpose of improved survey accuracy by statistical removal of correlated system errors.

transponder - A transmitter/receiver facility that will transmit signals automatically when the proper interrogation is received (25).

tribrack - Triple prism bracket.

tropopause - The boundary between the troposphere and stratosphere, usually characterized by an abrupt change of lapse rate; its height varies from 15-20 kilometers in the tropics to about 10 kilometers in polar regions (23).

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troposphere - That portion of the atmosphere from the earth's surface to the tropopause (23).

UHF - Ultra High Frequency; 300 MHz to 3 GHz.

ultrasonic - Pertaining to that band of frequencies above the audio-frequency range.

ultraviolet radiation - Radiation in the invisibile region of the optical spectrum; radiant energy rays that lie immediately beyond the violet end of the spectrum between the wavelengths of approximately 0.1 to 0.38 um (26).

underwater beacon (as used herein) - A device that is seafloor-moored or mounted to a submersible vehicle and either transmits a continuous signal or a responding signal to an interrogation from another source. This includes all those underwater devices that manufacturers variously refer to as responders, transponders, or beacons.

vector - A quantity which has both magnitude and direction and whose components transform from one coordinate system to another in the same manner as the components of displacement (23).

velocity - The time rate of change of position of a body; it is a vector quantity having direction as well as magnitude (23).

VHF - Very High Frequency; 30 to 300 MHz.

visible radiation - Radiation in that region of the electromagnetic spectrum to which the retina is sensitive and by which the eye sees; about 0.4 to 0.75 um in wavelength (26).

VLF - Very Low Frequency; 3 to 30 kilohertz.

wavelength - Physical distance covered by one cycle of a wave (26).

work function - The minimum energy needed to remove an electron from its thermal equilibrium energy state to infinity; usually expressed in electron volts.

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APPENDIX A

DEVELOPMENT OF LINES-OF-POSITION FOR POSITIONING METHODS

A.1   INERTIAL GUIDANCE METHODS

Reference: Initial terrestrial or celestial position

How Reference Obtained: Terrestrial references are obtained by using surveyed lines, bench marks, plumb bobs, and bubble levels. The references are in latitude, longitude, and altitude with respect to a particular datum (NAD27). Celestial references are obtained by the use of star trackers and radio sextants. The celestial sphere has an equator which is formed by the extension of the earth's equatorial plane, and has a non-rotating reference meridian which passes through the first point of Aries.

Method Used To Obtain Position Data: Accelerometers are used to detect accelerations of a vessel.

Relationship Of Measurement To Line-Of-Position (LOP): Any acceleration in a plane is detected and double-integrated with respect to time to determine displacement in that plane. Vector analysis provides bearing and range from an initial point in two or three mutually perpendicular planes.

Description Of LOP: LOP comprised of relative bearing and range to point of initialization from present vessel position.

A.2   LASER RANGEFINDER METHODS

Reference: Initial terrestrial position

How Reference Obtained: From previous surveyed lines and bench marks. Previous surveys with respect to NAD27 datum for conventional surveys or WGS-72 for satellite surveys.

Method Used To Obtain Position Data: Intersection of circular range lines from previously surveyed sites to rangefinder's position or intersection of circular range lines of several rangefinders to an object position.

Relationship Of Measurement To LOP: Time-of-transit for laser signal from rangefinder to object is measured and converted to corresponding distance that the signal travelled.

Description Of LOP: One circular range of constant radius originating at the position of the rangefinder.

A.3   PRECISION GYROCOMPASS METHODS

Reference: True North

<u>How Reference Obtained</u>: With a gyroscope

<u>Method Used To Obtain Position Data</u>: A gyrocompass does not provide position data. Instead, the system senses bearing with respect to true north as provided by the gyroscope. A collection of bearings from a vessel to previously surveyed objects can provide the basis for determination of the vessel's position.

<u>Relationship Of Measurement To LOP</u>: Direct

<u>Description Of LOP</u>: Bearing referenced to true north

A.4 RADIODETERMINATION METHODS

<u>Reference</u>: Position(s) of shore-based transmitting sites

<u>How Reference Obtained</u>: Conventional survey methods with respect to NAD27 datum or satellite surveys with respect to WGS-72 datum. Transformation between datums is possible.

<u>Method Used To Obtain Position Data</u>: Intersection of range lines at a vessel's position, with respect to the transmitting stations' coordinates.

<u>Relationship Of Measurement To LOP</u>: Time-of-transit for radio signal from transmitting station to vessel is measured and converted to corresponding distance that the signal travelled.

<u>Description Of LOP</u>: Both circular and hyperbolic LOP's are used for radiodetermination of position. The circular LOP has transmitting station's coordinates for its origin and is of constant radius. The vessel is determined to be at some point on the circle. The hyperbolic LOP results from difference measurements of the arrival times of signals from two transmitting sites. The vessel is determined to be at some point along the hyperbola.

A.5 SATELLITE METHODS

<u>Reference</u>: Orbital track of the six earth orbiting satellites with respect to the earth's center.

<u>How Reference Obtained</u>: User's equipment decodes orbital information in WGS-72 datum as transmitted by each satellite. Orbital information in satellite is updated every 16 hours by transmissions from a ground control station which combines the tracking data of four other ground stations in order to detect any changes in a satellite's orbit.

<u>Method Used To Obtain Position Data</u>: User equipment automatically tracks passing satellites, collecting satellite transmitted time marks and ephemeral data and making doppler velocity observations. This information is then processed in a user equipment computer to determine a succession of slant ranges from the user to a satellite. The slant ranges are then operated on to determine a three-dimensional position (location of user on face of the earth). Positioning can be refined by tracking successive satellites until such time as further passes do not appreciably refine the position solution.

Relationship Of Measurement To LOP: During precise intervals which are derived from time marks transmitted by a satellite, the user equipment counts the change in doppler frequency observed as a difference between the user equipment local oscillator and the received frequency as transmitted by the satellite and affected by the satellite velocity (and user's velocity if in motion). The doppler counts (per interval) are processed by a computerized data conversion routine which results in slant range differences between the satellite positions corresponding to the beginning and end of the counting interval. Combined with ephemeral data supplied by the satellite, the slant range differences are used to calculate the measured slant range between the user and the satellite. The measured slant ranges produce a measured position. A calculated position is determined in an independent computer operation based upon the ephemeral data transmitted by the satellite and the user's best estimate of his position. The measured and calculated doppler shift curves are then iteratively compared by successively updating the calculated curve (position estimate) until such time as the change in iterations is less than that defined by the user (for example, 2 meters).

Description Of LOP: Circular LOP having the position of the satellite as its origin and intersecting with the earth's surface at the user's location.

A.6 UNDERWATER METHODS

Reference: Position(s) of sub-surface moored acoustic beacons

How Reference Obtained: Initial placement of beacons. If beacon positions are not surveyed, subsequent surveying is relative only to the initial positions. Surveying with beacons may be indirectly tied to a geodetic datum such as NAD27 by using surface survey techniques to establish initial positions of the under-water beacons.

Method Used To Obtain Position Data: Intersection of range lines at a vessel's position, with respect to beacon positions.

Relationship Of Measurement To LOP: Time-of-transit for signal from beacon to vessel is measured and converted to corresponding distance that the signal travelled.

Description Of LOP: Both circular and hyperbolic LOP's are used in under-water positioning systems. The circular LOP has the coordinates of a beacon as its origin, with the vessel being at some point on the circle. The hyperbolic LOP results from difference measurements of the arrival times of signals from two beacons. The vessel is determined to be at some point along the hyperbola.